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FINAL

GEOLOGICAL REPORTS

OF

THE ARTESIAN AND UNDERFLOW INVESTIGATION BETWEEN THE NINETY-SEVENTH MERIDIAN OF LONGITUDE AND THE FOOTHILLS OF THE ROCKY MOUNTAINS,

TO THE

SECRETARY OF AGRICULTURE.

MADE BY

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
OFFICE OF IRRIGATION INQUIRY,
Washington, D. C., December 1, 1891.

DEAR SIR: I have the honor to transmit herewith my report as chief geologist of the artesian and underflow investigation, made under your direction, and by order of Congress.

The report is accompanied by those of my assistants, Prof. G. E. Culver, whose work has been in the Dakotas, Prof. L. E. Hicks, in Nebraska, and Prof. Robert T. Hill, in Texas and New Mexico. All are illustrated by maps, geological sections, and other drawings, that will help to the understanding of the subject investigated, viz:

The source, volume, and availability of the underground waters of most of the area of the Great Plains.

Besides acknowledging the encouragement received in my work from the Department in Washington, and my colleagues in the field, I wish to recognize the value of services and information spontaneously given throughout the broad area of the field of investigation, by citizens in their private character, as well as by State, county, city, and railway officials.

Effort has been made to give scientific accuracy of statement as free as possible from scientific verbiage, and I trust in this as in other respects the report will meet your approval.

I am, dear sir, very respectfully,

ROBERT HAY,
Chief Geologist, Artesian and Underflow Investigation.

HON. J. M. RUSK,
Secretary of Agriculture.

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ARTESIAN AND UNDERFLOW INVESTIGATION BETWEEN THE NINETY-SEVENTH MERIDIAN AND THE FOOTHILLS OF THE ROCKY MOUNTAINS.

By Prof. R. HAY, F. G. S. A.

GENERAL REPORT.

In beginning the investigation at the time of the year necessitated by the date (October 14, 1890) at which Congress passed the appropriation for this work, it became necessary to consider the most economic way of distributing the force available so as to make the season for field work in each part of the district as long as possible. The fact that assistants were to be had who had special knowledge of certain parts of the field made it desirable to use them at such time as would give the greatest scope for their abilities. It being already too late for any work in the Dakotas or northern Nebraska before winter, it was deemed best that the work to be done by Prof. Hicks and Prof. Culver should be postponed till spring or early summer of 1891. On the other hand Prof. R. T. Hill would be able to work out of doors nearly all the winter in Texas, and the neighboring parts of New Mexico, southern Colorado, and Oklahoma, while it would be possible for myself to do considerable field work in parts of Kansas, Nebraska, and Colorado before the winter set in. That plan, therefore, was decided upon and Prof. Hill began forthwith to visit parts of the region he was least acquainted with, the writer at the same time making reconnoissances, to connect districts visited during the short investigation of the previous season with each other and with places formerly known. In this way the chief geologist examined a large part of the Republican Valley in Nebraska and Colorado west of the one hundredth meridian, crossed the divide to the South and North Platte rivers, and returned through Colorado to northwest Kansas. Then, in company with Col. Nettleton and Judge Gregory, he made a journey across the State of Kansas on the one hundredth meridian. Afterwards he was on the same meridian on the Red River of Texas and, with Prof. Hill, made some reconnoissances in the Panhandle of Texas. Valuable observations were afterwards made in the foothills of the mountains from Trinidad to Pueblo, and these were only stopped by heavy snows in January. Later observations in the foothills were continued in the neighborhood of Colorado Springs, Golden, and Fort Collins, and west of Cheyenne in Wyoming. Then, in the spring, a journey was made, starting at Fort Collins, to connect with former observations on the plains in longitude 102, and the divide between North and South Platte was examined in several counties of Nebraska, and, crossing the former river at Camp Clarke, Box Butte County was explored and the descent of Pine Ridge

to the White River Valley was examined. Here Prof. Hicks was in company for a few days, he having then just taken the field. My journey was then extended to the Platte River Valley in Wyoming as high as Fort Fetterman, where for several days I had the advantage of associated work with Hon. Elwood Mead, State engineer of the State. Then a reconnoissance in the region where the Chugwater leaves the foothills, and the circle was completed to Cheyenne and to the South Platte in Colorado.

As with Profs. Hill and Hicks I also worked awhile with Prof. Culver; this was in the Black Hills of South Dakota. Then, going north, I spent the whole month of July in North Dakota, with some days in August. A short trip into South Dakota in February, and a shorter one as far as time is concerned in Montana in August, with a few short trips taken while engaged on my report, make up the record of my field work. The results of it will appear in the pages further on.

The work of Prof. Hill extended through nine months; that of Prof. Hicks through ninety of the long days of summer, and that of Prof. Culver through ninety-five. It should be added that each of these gentlemen gave additional time beyond that called for by their commissions—from ten to twenty days each—for the purpose of making the report more complete than it could have been in the exact time allowed.

The reports of these gentlemen herewith appended will speak for themselves. The information given may be relied on as accurate. Where there is deficiency it must be attributed to the largeness of the region investigated. It has been judged best to work out the various forms of the water problem in some districts thoroughly rather than pretend to do the whole region and to do it perfunctorily. The regions selected for this work are largely typical, so that persons residing in other similar districts may be able to use the information given, though the localities described may be different in some respects from those with which such persons are familiar. The descriptions by myself of the Republican Smoky Hill region and by Prof. Hicks of the region of the Loup rivers will be of service to persons residing in Wyoming, Southern Kansas, the Panhandle of Texas, and elsewhere on the Great Plains. The detailed account of the conditions under which phreatic waters are found in northeastern North Dakota will aid in an understanding of the phenomena in South Dakota and elsewhere where surface conditions are of the same glacial type. The account of the structure of the Black Hills by Prof. Culver is the key to the artesian conditions that may be looked for in parts of Wyoming, Montana, and elsewhere on the east flank of the Rocky Mountains.

It will be noticed by the readers of this report that technical words are very sparingly used. It has been the purpose to make it as readable as possible. Prof. Hill has given definitions of the technical words used by him, and to his list may be added the new word *phreatic*,* which is a very convenient term for underground waters which can be, or which it is hoped may be, reached by wells or other sub-ground works.

GEOLOGY OF THE PLAINS.

The geological terms necessary to a proper understanding of the whole of these papers, not previously explained, will have their names fully made known by the context.

* This word was first used in American hydro-geologic investigation by the Artesian and Underflow Office in 1890.

Rivers of the Plains. The Republican near Scandia, Kansas.

The strata in the earth's crust that it is necessary to know the names of in this investigation are arranged as groups and sub-groups, as follows:

Cenozoic:
  Quarternary or Pleistocene:
    Drift.
    Loess.
Tertiary:
    Pliocene.
    Miocene.
    Eocene.
Mesozoic:
  Cretaceous:
    Laramie.
    Montana.
    Colorado.
    Dakota.

Mesozoic—Continued:
  Trinity.
  Jurassic.
  Triassic.
Paleozoic:
  Carboniferous, including Permian.
  Devonian.
  Silurian.
  Cambrian.
Archæan:
  Schists.
  Gneiss.
  Granite.

The Montana formations are subdivided into Fort Pierre and Fox Hills, and the Colorado group has an upper member, the Niobrara and the Fort Benton lower, and these names will be occasionally used. The Niobrara in some regions has two members, the Yellow Chalk (upper) and the Blue Shale (lower). In the regions where they occur the inhabitants will recognize them by these names.

Some principal names are omitted in this, as the rocks they designate do not occur in the region, and the subdivisions of only one of the Mesozoic have been given as being all that is necessary. It is necessary to have names; these are not difficult ones and they have all a distinct signification, based on localities where the rocks they designate were first examined. The left-hand column has its terms based on the remains of life, fossils found in the rocks. These are sometimes of great importance in recognizing the order. All the following pages may be understood by the unscientific reader who will simply remember that these are names of strata in the order of their formation or age; the Quaternary are the newest formation, the Archæan the oldest, the others in their order. If the lowest is on the surface of the ground all the others are missing. They have either been eroded away or never were there. If any higher—for example the Dakota—are on the surface, all the others may be under, or some of them may be missing, as there were periods of erosion between some of these formations. On the flanks of the mountains the strata have been, by the forces of mountain-making, turned up on their edges; but throughout all the region of the Great Plains the strata are nearly level, a dip of only 5 or 10 feet to the mile being quite common, while dips as high as 100 or 200 feet to the mile are scarcely known. The plains' geology, then, is, on the whole, simple. When strata are found outcropping in ravines or bluffs, what is below them may be inferred with considerable certainty. The difficulty of geologic investigation is, that certain late formations are spread out in great sheets over thousands of square miles and hide the more regularly stratified formations below.

Erosion has cut valleys and ravines in these later formations, and the exposures of the older rocks must be sought for there.

To make this clear let it be understood that after the Cretaceous formations were laid down there was a period in which the region of the Great Plains was dry land and its surface was worn down by rivers, rains, and winds as the present surface is being worn, and that at that time the Rocky Mountains began to be elevated and bending of the

Cretaceous rocks was the result. The Black Hills were lifted about the same time with the same result. After the erosion the plains were again under water and Tertiary formations were deposited over a great part of the area. These are the softer beds that hide the old erosion. They are both Pliocene and Miocene in age, and some near the mountains may be Eocene. In northeast Dakota these do not seem to have been deposited, and later beds—drift and loess—cover up the underlying shales. In parts of Texas and Indian Territory erosion prior to the Tertiary deposits had reached down to Jurassic and Triassic rocks and the Miocene grit, of which frequent mention will be made, rests on those early Mesozoic rocks. In a few places in Kansas the same Miocene deposits rest on Carboniferous formations, erosion having removed all other deposits that might have been placed there before middle Tertiary (Miocene) time. The section on the one hundred and second meridian shows these tertiaries resting on bed rock of different ages.

The tertiary formations in the southern plains and the drift formations in the Dakotas have much to do with the water supply. All the phreatic waters available without very deep borings are found in them. Their arrangement is important to be understood. In the Dakotas and eastern Kansas and Nebraska there is a sandy marly formation known as the Loess, which in large areas overlies the drift and in others rests on bed rock of the district, Cretaceous or Carboniferous as the case may be. In the plains from the White River of Nebraska to the Panhandle of Texas there is a similar formation, varying slightly in texture and substance, as sand, lime, or clay predominate, which makes the smooth surface and the deep subsoil of the prairie. Its oldest parts are undoubtedly of tertiary age, but its formation lasted probably through the drift period, and its latest beds are probably contemporaneous with the Loess. We call it the plains' marl. Beneath the plains marl, with occasional exceptions, is a lower tertiary formation of Miocene age, which in this connection we shall call the tertiary grit. It has often been described. It is nowhere quite free from siliceous matter and mostly sand is present in quantity. In places it has become a gravel loosely held together, and again the material is more coherent, being a coarse gravel—some pebbles as large as the hand—but firmly cemented by lime and iron so as to form a firm conglomerate. Where the lime preponderates it looks when broken like chunks of hard mortar. Hence it is known extensively as the "mortar beds." Sometimes there is scarcely any sand, and the lime gives it a white smoothness that makes it serviceable for plastering cellars. In the northern parts of the area it is known as "plaster" and "native lime," and in the south it is the "terra blanca" or "white earth" of New Mexico and the Llano Estacado.

This tertiary grit, or simply the "grit," as we shall sometimes call it, whether as conglomerate, mortar bed, or gravel, is very absorptive of the rainfall where it is on the surface and very capable from its porous nature of retaining water, and in all the region named it is the source of the phreatic waters which supply the wells of the level or gently sloping high prairies which have for their surface the plains marl, whose less porous sheets cover much of the region. The gravels of the drift region of the north have a similar office and are the source of the supply in all wells that do not penetrate the bed rock below. In the drift region beds of clay above the gravels and similar beds—locally modified plains' marl—in the south produce artesian conditions that are repeated over large areas in the valley of the Red River of the North and are exemplified in the valley of Crooked Creek, in Meade County, Kans.

Rivers of the Plains. White River, Nebraska.

Red River Escarpment, Cañon Blanco, Texas.
Tertiary grit showing under the Plains.

Rivers of the Plains. Red River of Texas, in the Cañon.

Similar occurrences may be expected, and indeed are found, in the valley of the Pecos and elsewhere, but the phenomena will always be local. The Denver artesian wells are also from tertiary formations, but possibly of earlier age.

Of the deeper seated rocks the capacity for holding water depends on the same quality of structure, viz, looseness or porosity. Sandstones, therefore, and conglomerates rank first as water-holders. Prof. Hill has pointed out in very distinct form which are the water-bearing rocks in Texas, while Prof. Culver has shown that the sandstones of the Dakota formations are the holders of the artesian supplies in the James River basin, and these same Dakota sandstones give the artesian waters of Coolidge in the Arkansas Valley. The Jurassic beds are also largely sandstones, and they may be added to the Dakota beds as part of the James River basin supply. They may run out before they reach that region, but they are in contact with the Dakota in the outcrop in the Black Hills and also in the region of the Upper Missouri in Montana. There are incoherent (loose) sandstones, or perhaps it would be better to say hard compacted beds of sand in the upper cretaceous (Laramie) formations in west Western Dakota and Montana, which also hold phreatic waters where they are not broken into "bad land" topography, as on the Little Missouri. In the Yellowstone the conditions are such as to supply a limited area with artesian pressure. It is quite possible that such areas may be repeated.

In the region of Great Falls, Montana, the lower Cretaceous and Jurassic or Jura-trias sandstones are developed in favorable conditions for receiving the rainfall, and owing to the descent beneath higher Cretaceous shales easterly, probably could be made available for artesian wells in the Missouri Valley and to limited heights on the higher tablelands about and below Fort Benton. That they allow water to pass freely through them is seen by the enormous flow of the Giant spring, one of a series of springs in that region, which flows to-day as it was described by Lewis and Clarke eighty years ago. Their description is as follows:

> After descending the fall (Black Eagle or Upper Fall) and passing the Cottonwood Island on which the eagle had fixed its nest, the river goes on for 532 poles over rapids and little falls, the estimated descent of which is 13 feet and 6 inches, till it is joined by a large fountain boiling up underneath the rocks at the edge of the river, into which it falls with a cascade of 8 feet. It is of the most perfect clearness and rather of a bluish cast, and even after falling into the Missouri it preserves its color for half a mile. (Lewis and Clarke's Travels: Paul Allen's Edition, vol. I, p. 276.)

I estimate that this spring gives not less than 100 cubic feet per second, possibly much more. Its water is supplied from fissures in the porous strata and possibly may come from the river itself some miles higher up, and its position gives it an outlet into the river valley. The continuous strata below must convey much water by slow perculation and by worn fissures much further east, to augment the supply of the James River basin or to be tapped by springs or borings before it reaches there; by springs if impervious clay shales properly disposed force it to the surface, by borings if these shales hold it down as they certainly do for hundreds of miles.

Similar remarks apply to that part of South Dakota which lies east of the Black Hills. Experiment alone can certainly determine, but it is highly probable that artesian water may be had, at least in parts of the valleys of the Cheyenne and White rivers and in portions of the Mauvaises Terres.

Of the wide region from the Black Hills north and northwest to the Yellowstone and the Missouri, no examination has yet been made. So far as it is known to the reader he may apply remarks made concerning districts that resemble it. If deep-seated waters are found here connected with the montanal source which we predicate for the James River artesian wells, it will depend on the altitude whether they can be brought to the surface by hydrostatic pressure.

WYOMING.

The southeastern part of Wyoming belongs to the region of the plains, as described in Nebraska and Colorado. The plains are cut deeply by the North Platte and some of its mountain tributaries, as the Laramie and the Chugwater. The part east of these gives rise to some of the rivers of the plains. Notably on the north of the Platte near the Nebraska line are the head waters of the Niobrara (Running Water) and the White River. South of the North Platte, the plains proper attain their highest elevation. At Cheyenne they are 6,000 feet, and a long tongue west of that place, forming the divide between streams of the plains, running north and south, carries the plains, formations, principally the loose conglomerate, and a compact mortar bed, across the upturned Cretaceous and Carboniferous strata on the flanks of the mountains to rest on their primeval granite. This is the most notable instance of the actual contact of the plains tertiaries with the east slope showing that these late formations were laid down in waters that covered the plains region after the uplift of the mountains. That erosion has cut away the connection of the plains, formations, with the mountains is nowhere better shown than in the lower valley of the Chugwater, where the Tertiary gravel of the plains rises to a height of 1,000 feet on the east and the upturned Mesozoic and Paleozoic strata rise on the west in foothills from 1,200 to 1,500 feet.

A more detailed account of the surface of the region will show how the present conditions are related to the geology already presented.

TOPOGRAPHY OF THE PLAINS.

The region defined by Congress as the area within the scope of this investigation from the ninety-seventh meridian of west longitude to the eastern foothills of the Rocky Mountains is emphatically the region of the Great Plains. Forming as it does the greater part of the western slope of the Mississippi valley, no part of it is below the 1,000-foot level, except a part of its western limits near the Gulf of Mexico and some of its northeastern part in the valley of the Red River of the North. Technically then it is a high plain or plateau, or rather series of plateaus, but the English word plain has been practically applied in its plural form to the whole region, and the French word prairie and the Spanish llano have also been similarly used for its various parts. To us it will be the Great Plains; parts of it to the north will be spoken of as the high prairie, relatively to the neighboring valleys, and in the Panhandle of Texas we shall use the term Llano Estacado, palisaded or walled plain, from its abrupt outline to the valley of the Canadian and that of the Pecos.

A large part of the region has been characterized as the American Desert. Yet its grassy surface has been invaded by agricultural set-

tlers who in a few years demonstrated the capacity of the alleged desert to grow abundant crops. A few more years of less rainfall again set up the claim that it is not suited to agriculture, but the proved fertility of all its soils from Dakota to Texas has made the settler of the Anglo-Saxon race or of any other of the many peoples included in the name American, loath to yield back to nature so glorious a domain. The rainfalls often fail for three out of five years to be sufficient for growing crops at the critical time of greatest heat in July or June. But the settler is persistent in desiring to know whether there is not water below ground sufficient to eke out the rainfall so as to insure average agricultural success. To enable the people who desire to be informed about this vast part of their country, one-fifth of its whole area, to understand the problems to be propounded, a somewhat general account of the region must be given, with such typical details as will give explicitness to the generalizations.

Looking then at the region as a whole, either by studying the best maps or traveling over its various parts, the investigator can not fail to note two prominent facts: (*a*) While the region is without mountains and has but few hills, there is a general increment of elevation westward or west by north. The 1,000-foot contour line crosses the Arkansas River about the ninety-seventh meridian and the Missouri River 200 miles farther north, near the ninety-fifth meridian. The other contour lines are approximately parallel to this, but do not rise so rapidly in the Missouri Valley as in the Arkansas. On the latter, the 2,500-foot level is reached at the one hundredth meridian, and 4,000 feet is crossed not far from the one hundred and fourth meridian. Farther north, between the Smoky Hill and Republican rivers, the 4,000 feet is reached at the one hundred and second meridian and the plains generally rise to a greater height to the northwest, reaching over 5,000 feet in northern Colorado. Again, the valley of the Platte cuts down the level as does the Arkansas Valley, and in Wyoming the plains rise to between 6,000 and 7,000 feet. South of the Canadian there is also increment, the Llano Estacado of Texas being 4,000 feet in the region of the one hundred and first meridian. (*b*) The rivers of the region are of two classes; note them. The Missouri, the Platte, the Arkansas, the Canadian, and the Rio Grande all have their sources in the mountains to the west. Their courses are across the plains, east by south and southeast. The most cursory examination of the map will show that there are numerous other rivers whose beginnings are not in the mountains. The mountain rivers before mentioned get around their heads and shut them off from any share in the snow-melting of the high Rockies. The short mountain river, Cheyenne, whose source is the Black Hills, effectually cuts off the White River from mountain waters. The Niobrara and Loup rivers in Nebraska are rivers entirely of the plains. The Smoky Hill and Republican group have their head waters in sandy, gravelly arroyos between the one hundred and first and one hundred and fourth meridians, the trenches of the South Platte and the Fountain, a tributary of the Arkansas, lying between them and the foothills of the mountains. So the Pecos and the Red River are cut off from montanal connection by the higher valleys of the Canadian and the Rio Grande. Other rivers of Texas are seen to have similar origin, though some have what may be called a mountain supply, as they rise near the isolated mountain groups of the Sierra Blanca and the Wichita mountains, as the Cheyenne above mentioned takes the waters of the Black Hills.

These rivers of the plains then form a topographical feature of great

importance and, as we shall see farther on, directly related to the water that may be available for irrigation. They have their origin and course entirely in the plains. The sides of their valleys show the outcrops of the rocks which form the foundation of that region. This is true also of the mountain streams that intersect the plains. In the plains they have the characteristics of rivers of the plains, in addition to the quantity of water they carry from the mountains.

Between the Missouri and the Canadian no river valley, except those of the mountain rivers near the mountains and the valley of the White River in northwest Nebraska, is more than 500 feet below the highest point of the plains immediately north or south of it; usually they are much less. Almost invariably the steep side of the valley is the south side and the tributary valleys there are shorter than those on the north side. These tributaries have all an eastward trend, some more east than south or north. The profiles given show this, and if all the smaller tributaries were marked on the maps it would be conspicuous there.

The cutting off of the rivers of the plains from the mountains, as mentioned above, produces another marked topographical feature. The plains have a steep west escarpment. This is not manifest everywhere, for in places it is hidden by sand hills abutting against it. In others a gentle slope is seen. Still, the steep westerly front of the plains is a marked feature through great distances. It is conspicuous north and south of Colorado Springs, and is seen in the neighborhood of Denver. The traveler by the Cheyenne Northern Railway going southward from the confluence of the Laramie River and the Chugwater sees to the west the bold mural front of the foothills of the Laramie range—the upturned Dakota sandstones resembling nearly vertical trap dikes for long distances, and on the other side there is a front of what seem rocky ledges lying horizontally, or nearly so, and rising nearly as high as the foothills. These rocky ledges are the hard conglomerate parts of the immense Tertiary gravel deposits of the plains, under which are beds with few pebbles and much lime and clay, which in places stand alone as white walls, suggesting ruined castles and cathedrals and sometimes making great mounds and promontories. These gravel and marl mortar beds are the west escarpment of the plains. As you proceed towards Cheyenne you rise in the valley to near the top of the high plains, having only a very slight abruptness to the east, and the mountain escarpment is further away. South from Cheyenne, on the Denver Pacific, the same thing is seen recurring, the eastern escarpment more distant is seen beyond the valley of the South Platte, which here has its upward southerly trend well developed. The escarpment is also accompanied by some outliers, of which Fremonts Buttes, rising 700 feet above the Platte Valley southwest of Sterling, are conspicuous examples. The Burlington and Missouri Railway, 3 miles west of Akron, makes a big cut to begin its descent from the plains to the sand-hill regions, which there abut against them.

This western escarpment is also conspicuous on the west side of the Llano Estacado in Texas, as is shown in the report of Prof. R. T. Hill. The position of the Black Hills also gives, in western Nebraska, a northern escarpment to the plains of that region. Pine Ridge is the northern front, and it rises boldly 900 feet above the White River Valley. Some of the outlying buttes are 700 feet above the river.

The very slight depression of Crow Creek at Cheyenne, in Wyoming, is all in the plains formation, and in the tongue of land up which the Union Pacific Railway runs west from Cheyenne to Granite Cañon we have

Pine Ridge Escarpment, Northwestern Nebraska.

perhaps the sole illustration of the fact the plains formation did once rest against the base of the mountains. We see here the plains sloping upward and their mortar-bed conglomerates lying over the upturned foothills strata and reaching beyond to rest on the granite. Fragments of the plains mortar-beds also show at the entrance of the Royal Gorge above Cañon City, and traces may be noted at other places on the flanks of the mountains, but with these exceptions the great fact is that the plains formations are now cut off from all contact with the mountains, and for long distances they present a front to the west of steep, bold bluffs.

WATER SUPPLY OF THE PLAINS.

Though this investigation is mainly concerned with the subterranean waters of the region examined, yet a consideration of the visible waters in the beds of rivers and creeks is to some extent a necessary preliminary, as in some instances there is a direct relation between the invisible sources of springs and wells and the visible water running in the river beds. A consideration, therefore, of the river systems of the plains region is very important if a correct understanding of the water supply is to be obtained. Having, then, already presented some general account of the region topographically as well as geologically, a more detailed account of the hydrography is in order.

We have already noted, and it will be seen even by a cursory inspection of the map, that there are many rivers whose source is not in the mountains. The great rivers—Missouri, Yellowstone, Platte, Arkansas, the Rio Grande, and the Canadian—have sources well up in the high valleys of the main range of the Rocky Mountains, and they also have important affluents carrying to them the waters of the foothills. These streams carry the melted snows of the mountains in deep channels across the plains to their great outlet in the Mississippi. There are more numerous rivers which, being shorter, have no such source for their waters and yet are no mean affluents of the Father of Waters directly, or by increasing the volume of the mountain streams themselves. Such streams are the James and Red rivers in the Dakota system, the Loup rivers in Nebraska, the Republican and Smoky Hill, the Cimarron, the Red River, the Neuces, and Brazos, besides many others tributary to these and also tributary to the greater mountain streams.

These rivers are distinctively rivers of the plains. They have both their source and their course there. We wish to give a clear impression of them, and it must be borne in mind that the streams that come from the mountains and course through the plains are similar in their local surroundings, and therefore much of what is said of the former will also be true of the mountain fed rivers.

Looking again at the map, it will be seen that the mountain-fed affluents of the large mountain streams almost surround the head waters of the rivers of the plains. The latter are shut off completely from having any share in the melting of mountain snows. Observe how the Rio Grande and the Canadian get round the heads of the Red River and the Pecos. Notice how the Platte and the Arkansas, with its tributary, the Fountain, cut a trough between the mountains and the head waters of the Republican and Smoky Hill and their numerous affluents. This is repeated on a smaller scale in Dakota, where the Cheyenne takes all the streams from the Black Hills and leaves the White River to be a river of the plains. Again the process is repeated by the plains' rivers themselves, the Neosho being so headed by other affluents of the Missouri and Arkansas.

Remember the slope of the country is to the east, but that in going from the plains to Denver or Pueblo there is a descent into the valleys of the mountain rivers. It is in the high plains east of the one hundred and fourth meridian that the rivers of the plains have their source.

We have described the geologic formations of the plains as Tertiary and post Tertiary. These terms will have to be used in describing the river valleys. In the eastern part of the region some of the river valleys in their origin are vastly older than the Tertiary period, but in their present form no part of the plains is older than late Tertiary or even post Tertiary. The river valleys are *new channels* cut by erosion since the close of the Tertiary period, though many of them are on lines that had been eroded before the last Tertiary formations had been deposited.

All water-bearing rocks, then, of the later formations on the plains have their water from the rainfall of the region. The plains' marl as formerly described, and the immediately subjacent Tertiary grit, take in what of the rainfall is not evaporated or hastily run off in the storm-used arroyos. Where the grit is exposed it readily absorbs moisture. Probably three-fourths of the rainfall sinks into it. A heavy rain scarcely seems to wet its surface, so rapidly is it absorbed. The areas of such exposure are, however, small as compared with the whole region, though in the aggregate they are thousands of square miles. The plains marl absorbs much less rapidly and more runs away, but the area of its exposure is immense, and since its surface has been broken by the plow to the extent of hundreds of thousands of acres, it is much more extensively absorptive of the precipitation, which it conveys downwards to the grit lying below it. The grit, then, is the great water holder of the plains. It may be considered as an immense reservoir wherever it is under cover. Where valleys are cut into it, springs are the signs of its presence; they are the overflow of the subterraneous basins. When the valleys have cut through it, the aggregation of the springs makes streams. These streams are the rivers of the plains. Not one of them has permanent water in its channel till it has cut deep into the grit. In the Panhandle of Texas the Red River cuts hundreds of feet deeper into the body of the plains than the base of the Tertiary grit, but very little water enters the stream from springs below that base. It may be that some sandstones below (probably Jurassic) contribute something, but a ramble of miles over these broken surfaces in rugged cañons showed only a few very small springs. In a large part of the plains area the grit rests, as we have already shown, on shales, which are largely argillaceous, and so its base is impervious to water.

The Tertiary beds also thicken as we go north and northwest, and in the region of the White River the grit is underlain by a series of Tertiary clays and marls, which throw out springs from their upper surface. They are as impervious to water as the subjacent cretaceous shales.

The plains' marl has some clay in it. In weathering much sand is left behind, the clay being dissolved out and the lime leached away. The weathering of the grit also leaves much sand behind. Near the mountains the weathering of the Laramie formations forms also great quantities of loose sand. The sand from all these sources, which is carried down the valleys of rivers of both mountain and plains origin, is acted on by aërial currents and carried up the slopes of the divides, forming the eolian dunes whose position has been previously noted and whose aggregate area is considerable. These sand dunes are more receptive of moisture than even the exposed surface of the grit, and very little of the rain falling on them is given off by direct evaporation. Some of it is retained and makes damp or wet lake-like areas, which have a more

Erosion, showing Tertiary Grit on the Plains.

or less impervious floor, and in dry years the hollows of the sandhills have yielded crops when the level high prairie has been sterilized by drought or hot winds.

But it is probable that most of the precipitation absorbed by the sand-hills finds its way down to the reservoir of the Tertiary grit.

Between the one hundred and second and one hundred and fourth meridians many of the rivers of the plains have not cut down to the grit. Few have permanent water in their channels. They are gravelly or sandy arroyos where water may be had by digging. The whole of this region may be therefore considered as gathering ground for the supply of the underground reservoir in the grit, except in the channels cut across the region by the mountain-fed rivers. East of the one hundred and second meridian most of the streams have cut below the grit—the Republican as far west as the one hundred and third—and the area of the valleys of the rivers must therefore be deducted from the area of the gathering ground of the great grit reservoir. The water supply of these valleys will be separately treated.

This great underground reservoir—or, more correctly, series of reservoirs—has its source of supply in the rainfall of the region. This is the region of deficient rainfall—deficient as to the supply of rain for agriculture. Is the reservoir, therefore, large enough to give back for irrigation what has escaped from the surface, and so make good over a sufficient proportion of the area the deficit of precipitation? Is the rainfall sufficient to replenish the reservoir as fast as its waters may be so used for irrigation?

Answers to these questions approximately correct are only partially possible at present. Observations on the quantity of rainfall have only been made at comparatively few places widely separated, and no experiments at all have been made on evaporation as related to the absorptive character of the soil. Still it is possible to form some opinions that will serve as working theories till more facts are accumulated.

Prof. Van Diest in his report on artesian wells (Senate Ex. Doc. No. 222, 1890, p. 96), says:

> It is not an exaggerated estimate to suppose that half of the rainfall in eastern Colorado, and probably also in eastern New Mexico, sinks into the ground. In eastern Colorado this will not be less than 5 inches over an area of 32,000 square miles, which is equal to 784,080 cubic feet of water disappearing per minute. If this amount could be redeemed from the subsoil it would be sufficient for the irrigation of 1,200,000 acres or one-seventeenth part of the above-named area.

As the rainfall at Denver and in its longitude is about 13 inches per annum, and the rainfall in western Kansas and Nebraska is 18 to 20 inches, Prof. Van Diest's estimate is as he says certainly not an exaggeration, and between the one hundred and first and one hundred and third meridians—at least north of the Arkansas—the average quantity absorbed by the surface and carried down to the underlying grit is not less than 30,000 cubic feet per acre, which with the rainfall would suffice if restored to the surface to irrigate probably twice as great a ratio as that suggested by Prof. Van Diest. We shall have something to say farther on about raising this to the surface, and the engineering report will discuss more completely the various feasible means.

That the Tertiary grit is a water holder of great importance has been inferred from its porous nature, and the impervious nature of the formations immediately beneath it. That it is actually so is known by the wells that all over the plains have been dug or bored to it. The level region of the Texas Pan Handle has water from wells; the plain between the Cimarron and Arkansas has water; the divides between the

the Republican and Smoky have hundreds of wells; away up on the Niobrara the high prairie has wells. They vary in depth, but each divide has a uniform depth for long distances or they increase gradually in a given direction. At Washburn, Tex., they are 150 feet deep; at Richfield, Kans., and east thereof for 70 miles they are 80 feet deep. North of the Frenchman, in Nebraska, they are over 200 feet on the Colorado line, increasing to over 300 feet 40 miles east.

The wells throughout the region that reach the grit are considered inexhaustible; that is, they have so far stood every strain that has been put upon them. Im some cases hundreds of cattle have been constantly watered from one well with a windmill to fill the troughs, in others a thousand sheep. At Cheyenne Wells all the railway shops and all the town is supplied from this source by two wells 260 feet deep, the water being lifted by steam pumps working day and night.

Where a windmill already exists some few acres may be irrigated. A more powerful windmill pump and a small—one or two acres—reservoir would allow more water to be raised, and the farm redeemed at once from aridity and mortgage. It is not expected that more than 15 or 20 acres can be thus irrigated on any quarter section, and on large areas the average will not perhaps be more than ten acres; but the high divides and the body of the great plains must be thus irrigated if any large part is to be redeemed in the next quarter of a century. Energy and some capital will do much in ten years. The underflow of the valleys and arroyos will allow their neighboring slopes to be irrigated from that source; but this underflow will be discussed further on.

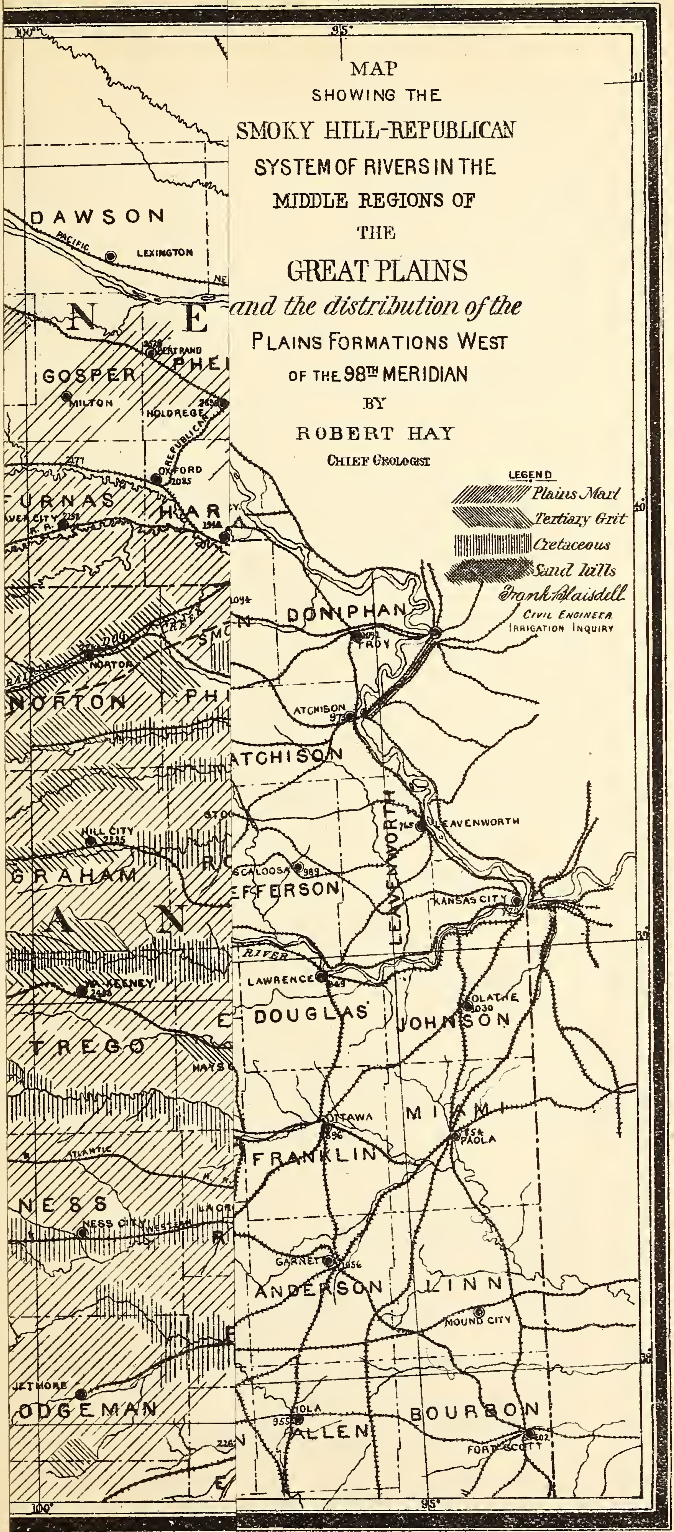
We have seen that the water in the Tertiary grit, buried from 50 to 300 feet below the plains and cropping on the sides of ravines in gushing springs, is the main reliance of the plains region; it is the sole reliance of immense areas lying back from the valleys, the only reservoir on which these wells can draw to irrigate the land. We have seen that it is the source of the waters of the rivers of the plains, and adds to the volume of those whose origin is in the mountains. We have shown that its source is the rainfall of the region, varying from 18 or 20 inches on the one hundredth meridian to 12 or 14 inches on the one hundred and fifth. These conclusions are based on observations made from the Rio Grande to the Yellowstone. The facts have been slowly and with much pains accumulated. The result is stated in a few words.

To give the reader—the Western settler or Eastern investor—an insight into the heart of the matter, we will treat in detail the facts of one sub-region, a typical part of the Great Plains.

THE SMOKY HILL—REPUBLICAN AREA.

The region which is the basin of this river system has been selected for this detailed description because of its typical character. It forms part of three States. It has much high, level prairie. It has valleys cut to and below the grit. The reader should make constant use of the map which illustrates this part of the subject. The necessities and the possibilities of the region will be made plain. Colleagues of the writer will give similar information about other river basins. The total will show a multitude of facts and justify the generalizations about the Great Plains.

The Smoky Hill River and the Republican River come together some ten miles east of the ninety-seventh meridian, at Fort Riley, in Kansas. Together they form the Kaw or Kansas River, which empties into the Missouri at Kansas City. They were formerly spoken of as the Repub-



MAP
SHOWING THE
SMOKY HILL-REPUBLICAN
SYSTEM OF RIVERS IN THE
MIDDLE REGIONS OF
THE
GREAT PLAINS
and the distribution of the
PLAINS FORMATIONS WEST
OF THE 98TH MERIDIAN
BY
ROBERT HAY
CHIEF GEOLOGIST
LEGEND
Plains Marl
Tertiary Grit
Cretaceous
Sand hills
Frank Blaisdell
CIVIL ENGINEER
IRRIGATION INQUIRY
DAWSON
LEXINGTON
PACIFIC
GOSPER
MILTON
HOLDREGE
BERTRAND
REPUBLICAN
OXFORD
NORTON
GRAHAM
HILL CITY
TREGO
WA-KEENEY
NESS
NESS CITY
JETMORE
DONIPHAN
TROY
ATCHISON
LEAVENWORTH
JEFFERSON
KANSAS CITY
LAWRENCE
DOUGLAS
JOHNSON
OLATHE
OTTAWA
FRANKLIN
MIAMI
PAOLA
GARNETT
ANDERSON
LINN
MOUND CITY
IOLA
ALLEN
BOURBON
FORT SCOTT
RIVER
95°
100°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IRRIGATION INQUIRY
NEBRASKA
KANSAS
COLORADO
SMOKY HILL-REPUBLICAN WATERSHED
Basin

Rivers of the Plains. Reservoir fed by Underflow, Frenchmen's Creek, Chase County, Nebraska.

lican and Smoky Hill forks of the Kansas River. Their size fully jusfies the dropping the word "fork." The high prairie of eastern Colorado is where they both have their origin. A short drive takes you from springs in the bed of the South Fork of the Republican to desolate arroyos descending to the North Fork of the Smoky. There is permanent water in the beds of the north and south forks of the Republican west of the one hundred and second meridian, but not in that of the middle fork (Arickaree), whose springs are soon lost in the deep gravel and sand. Neither is there water in the North or South Smoky, though there is within a dozen of miles further east. These statements illustrate the fact that the rivers of the plains, having water have cut deep into or below grit before they have permanent water. It is also true that these rivers do not have permanent water in sight till some distance below where it might be expected from the position of the grit. This is because the channels are so filled with sand and gravel—the débris of the two Tertiary formations—that the water is out of sight for miles and shows at last by virtue of its quantity and the nearness of the subjacent shales or other bedrock of the region. In Cheyenne and Sherman counties, Kans., gentle depressions are the beginnings of the valleys which further down have the Beaver and the Sappa creeks, which run northeast to the Republican. In Thomas County similar depressions are the heads of the Prairie Dog, the Solomon, and the Saline, the first also running to the Republican in Nebraska while the others, running nearly straight east, eventually reach the Smoky. The watershed between the two main rivers of the system is therefore (as indicated in the map by a broken line) an irregular line through the south part of the northern tier of Kansas counties. In places this line is very sinuous, where, by headwater erosion the affluents of the streams have worn away the highest prairie and the drainage is interlocked. The phenomena of interlocked drainage is repeated in the divides of smaller streams.

As with the main streams, so with these tributaries, there is no permanent water till they have cut through the grit. With the Prairie Dog and Saline this is near the Thomas-Sheridan County line. With the Beavers and Sappas (there are several forks of each), it is somewhat further west in Rawlins or Cheyenne. The Smoky has only one important affluent from the south, the Beaver in Scott County, but the area of the joint basin is considerably enlarged by northern affluents of the Republican. Of these the most noticeable are the Frenchman (or Whitemans) Fork, the Red Willow, and the Medicine. The first of these merits special description. Like the others above-mentioned, the Frenchman has dry arroyos for its upper water courses for a score of miles or more, and in these are deep beds of coarse gravels and sands, in which at variable depths is found abundance of water which probably has a slow flow in the general direction of the valley. This is the condition of the main valley through all its Colorado extent, except that some 30 miles southwest of Julesburg there are in it two pools of water which are said to be always clear and cold. As these pools were on a well-worn cattle trail heading towards Julesburg, they are known as the Julesburg water holes. Which of the various phenomena dwelt upon as to the position of these western waters account for the permanent water in these holes, will, perhaps, be apparent as the discussion of them proceeds. Near the Colorado-Nebraska line the main channel of the Frenchman begins to have running water, and in a very few miles the stream attains considerable volume. It runs thence to its confluence with the Republican at Culbertson with undi-

minished force. A remarkable fact, about which the testimony of all settlers is uniform, is that, while not diminishing, *the volume of the Frenchman never increases.* The heaviest local rainstorms or rapid melting of snows do not raise its surface an inch. Perhaps long-continued, accurate observations, might show greater variation than is indicated in this account, yet the phenomenal fact is true that in the matter of floods the Frenchman is unlike its congeners, the rivers of the plains, wherein rapid and disastrous floods are as well known as their average scarcity of water. Without here affirming absolutely the causes of the steady flow of the Frenchman, I will note one or two facts that have a bearing on the matter: (*a*) The bed of the Frenchman, or rather its valley altogether, from where it has its first water, a few miles above Champion to near Palisade, is cut into, bounded by, and based on the Tertiary grit, which in this region attains great thickness, probably reaching in places 200 feet. (*b*) In the region of many of its affluents, all gravel beds, the Tertiary grit forms over hundreds and thousands of acres the floor of the slopes, and of considerable parts of the high prairie itself, without the usual covering of the plains marl. It is evident, then, that the porosity of the grit readily absorbs the rainfall, rather than allows it to run off in floods, and that which first reaches the stream from this cause is followed by the water which has had longer percolation through the marl. (*c*) The last 15 or 20 miles of the river's course is at or below the bottom of the grit, so the large body of sandy alluvia may take much of the water as an underflow contributary to that of the Republican Valley.

Cutting down through the water-bearing grit, rivers of the plains reach in their easterly course what may be called bed rock. Usually this bed rock is of much softer material than most of the water-bearing grit. It is the shale, the chalk, or the limestone of the Cretaceous formations. South of the Arkansas the Dakota sandstones and shales are immediately subjacent to the grit, and farther south still the Jurassic [or the Neocomian] is in that position, while farther east the Jurassic is mostly missing, as in the valleys of the Canadian and Red River east of the hundredth meridian and the Triassic "red beds" are found there lying immediately under the Tertiaries. On the high plain of West Texas—the Llano Estacado—the Red River has cut a gash 1,000 feet deep, which shows this descending order of formations:

Plains' marl.
Tertiary grit.
Jurassic.
Triassic.

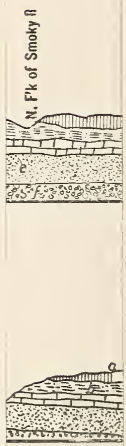
Taking a series of exposures in river valleys we see how they vary from this and approximate it as we come from the north. In Norton County, Kans., near the fortieth parallel on the one hundredth meridian, the Pairie Dog Valley shows this order:

Plains' marl,
Tertiary grit,
Yellow chalk, } Niobrara.
Blue shale, }

Farther west towards the Colorado line in Kansas and Nebraska the section is about this:

The plains' marl.
Tertiary grit.
Carbonaceous and clay shales (Fox Hills or Pierre).

Thompson's Butte, South Dakota. Tertiary Grit left by Erosion.


N. F'k of Smoky R

On the White Woman, farther south, as also on the Smoky, in Kansas, the order runs—

Plains' marl.
Tertiary grit.
Chalk, } Niobrara.
Blue shale, }

On the Arkansas the section is—

Plains' marl.
Tertiary grit.
Benton ledges.

On Bear Creek it is—

Plains' marl.
Tertiary grit.
Dakota.

On the Cimarron we get—

Plains' marl.
Tertiary grit.
Trinity sands.

(See profile and section of the 102d meridian.)

The chalk and the soft limestones will hold considerable water, and sometimes the springs of the regions, where these outcrop, come out of them, or at the bottom of them, running off the underlying shale. The Niobrara, having more shale than chalk, is mostly a poor water-holder, and the waters of the river valley where the shales are cut, are all in sight or hidden in river alluvia. The north and south profiles and geologic sections will make this part of the subject readily understood, and the channels of the streams deeply cut into the subtertiary shales are seen to cut off connection between the sheet water of one divide and that of others, and this most decidedly as we proceed eastward. The dip of the subtertiary strata is not easy to make out in the region west of the one hundredth meridian, because of the covering of the Tertiaries, but exposures in the Arkansas Valley, in the Solomon Valley, and in the Republican Valley in Nebraska show slight inclination to the south and east. In the whole of the region the most important and most numerous springs are on the north sides of the larger valleys, and in the smaller lateral valleys on the same side. The dip, therefore, with some undulations, is probably on the whole to the south of east, which is the general slope of the surface of the country, as noted in the chapter on topography, making a general slope from Wyoming to the east of the Indian Territory.

It will be seen, then, that the rivers of the Smoky-Republican series are aligned to this general slope and stratigraphic dip at somewhat diverse angles. The southern forks of the Republican and some of the tributaries farther east on the same side run north of east. This is somewhat across the dip. That this fact is related to the character of these streams differing from those of the North Fork of the Republican and the Frenchman is quite possible, though the relation is not made out, and that it exists at all may be doubted, as there is marked resemblance between the valley of the lower Prairie Dog and that of the Red Willow (on opposite sides of the main stream and running nearly at right angles to each other), both in depth and narrowness of the channels and the quantity of water.

In treating of this area of the Smoky Hill-Republican basin, the high prairie between the river valleys must be specifically noted. They are of all the kinds referred to in the topographic chapter. Between the

Fig. X. Profile and Section from the Platte River to the Arkansas nearly coincident with the eastern boundary of Colorado, (102nd Meridian), showing the surface developement of the "Plains' Marl" and the position of the water-bearing "Grit."

a. Plains' Marl. b. Tertiary Grit. c. Montana formis. d. Colorado Gp. e. Dakota Group. f. Trinity Sands. g. Red Beds.

Scale { 1—507000 Horizontal
{ 1— 9600 Vertical

Fig. XI. Profile and Section from across Kansas on the 100th Meridian showing more rugged topography than further west and the outcrop of the subjacent Cretaceous formations making breach of continuity of the water-bearing "Grit." Scale and connections same as in Fig. X.

By Robert Hay

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highest arroyo of the Frenchman and the head waters of the North Fork of the Republican is a region of sand dunes with many basins having no outlet. A little east by north in Nebraska on the north side of the Frenchman is as smooth aprairie as is seen in the West, and this too has its inclosed basins. Farther south the divides are narrower, but in eastern Colorado between the forks of the Republican are fine examples of the level high prairie with basin-like depressions having no outlet. East of the one hundred and first meridian the narrow divides have the same smooth surface on top; and taken in the direction parallel to the bounding valley, a plow might be run without lifting from 50 to 100 miles. Between the 100th and 102d meridians the valleys and their immediate slopes occupy fully half of the region, but between the latter and the 104th the high prairie occupies fully three-fourths of the region, and a large part of the other fourth is gently rolling toward narrow, deep, but not precipitous, valleys.

In all the valleys water is found at comparatively small depths, 3 or 5 feet to 50 or 60, according to the texture of the various alluvia. On the high prairies it is different, and on the higher edges of the slopes occasional wells are found without water. On the divide between the Stinkingwater and Frenchman the depth to water in wells is 200 to 240 feet near the Colorado line, increasing to 350 feet, 40 miles east. South of the Frenchman the prairie wells are 150 to 250 feet. On the south of the Republican the divide between Sappa and Prairie Dog has wells from 75 to 85 feet deep. Between the Sappa and Beaver the wells are a little over 100 feet on the average, while between the Solomon the Saline and Smoky, a little less than 80. East of the one hundreth meridian each main stream has many tributaries, and the divides are narrower, accompanied by more irregularity in the depth of the wells, and there is more outcrop of the cretaceous strata where scarcely any water is found. There are, however, sufficient examples of the grit as the main water-bearing stratum which serve to illustrate the facts, which are more uniform farther west.

This grouping of rivers and the interfluvial plains is illustrative of the condition of rivers and the relation of their water supply from Texas to Dakota. The group included between and including the North and South Forks of the Red River of Texas differs from the group described only in greater elevation of the plains cut into and the geologic formations subjacent to the Tertiaries. The Loup rivers and the northern Cimarron, the Niobrara, and the White River are in many respects the same, the last rivaling the Red River in the depth of its valley. The depth of wells in the interfluvial spaces, the relative height of the water of these wells as related to that of the river valleys, are the main differences that interest the reader of this economic investigation, and this is well shown in the profiles given in Col. Nettleton's report of January, 1891. The variation of rainfall, too, must be taken into account, and a fair estimate then may be made of the expectation of the number of acres for which water is available for the irrigation either of the high lands or valleys of any of the river basins of the plains.

The volume of some of the rivers of the plains is given in the following table, with that of the Missouri and North Platte, for purposes of comparison:

River.	Locality.	Date of measurement.	Volume (cubic feet per second).
Missouri	Fort Benton, Mont	Aug. 12, 1891	20, 700
North Platte	Douglass, Wyo	June 3, 1891	10, 130
Do	Camp Clarke	May 29, 1891	8, 075
White River	West of Chadron	June 1, 1891	123
Loup River	Near Columbus	June 24, 1891	7, 065
Red Willow	Red Willow City		52
Frenchman	Culbertson	Dec. —, 1889	310
Do	At Palisade	Dec. —, 1889	240
Republican	Scandia, Kans	June 10, 1891	1, 534
Do	Junction City, Kans	June 15, 1891	2, 045
Smoky Hill	Ellsworth	June 8, 1891	360
Do	Southwest of Junction City	June 15, 1891	961
Kaw	Fort Riley	June 18, 1891	6, 961
Solomon	Beloit	June 19, 1891	270
Saline	Lincoln	June 8, 1891	125
Running Water	Dawes County, Nebr	Sept. 4, 1887	98

This table, while giving the flow of the rivers approximately correct for the dates at which they were taken, suggests also defects in our knowledge on this subject. The measurement of the North Platte at Douglass was made by Prof. E. Mead, the State engineer of Wyoming, the writer assisting. The river was high, but not at its highest. At that point there is little or no underflow, as the river is cutting bed rock, or having the bed covered but thinly with sand or gravel. The high water had not reached Camp Clarke when the measurement was made there by myself and Prof. L. E. Hicks, of Nebraska, and at that place there is a wide sandy valley and stream bed which must have considerable underflow. Again the flows of the Republican and Smoky Hill, taken June 15, a few miles east of the ninety-seventh meridian and some miles above their confluence, give a total of 3,000 second feet. A few days after the measurement of the Kaw (the united Smoky and Republican) gave more than double that within half a mile of the confluence, much rain having fallen in large parts of the area of the basin in the interval. Still the Kaw has been much higher than at that date, and I estimate that the Smoky as far west as Ellsworth, when in flood, carries more than ten times what it gave at the time of measurement there. A similar estimate would probably be true of the Republican at Scandia. The width of water was 196 feet, with an average depth of 3¼ feet. An increase of 1 foot in depth would double the width of the stream, and it has been 6 feet higher than at that time. The large volume of the Loup is also lagely increased in time of flood, as is intimated in the report of Prof. Hicks, who made the measurement. The measurement of the Missouri was made when it was 2 feet above low water, and it was nearly 6 feet higher in July. It was a foot lower in September. The measurements of the Frenchman were made by Mr. Wildman, of Culbertson.

The measurements of the Loup, Republican, and Smoky were made where they had passed out of the drier parts of their courses. Their waters to be used for irrigation, would have to be tapped much farther west and before they have acquired such volume. The tributaries of their lower courses come out of cañon-like valleys, where they are very slightly available for irrigation.

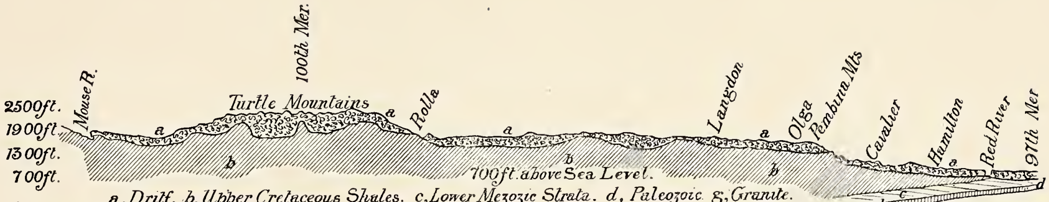
NORTH DAKOTA.

In North Dakota there are three classes of artesian wells arranged in order of their depth and pressure.

At Jamestown, the well, the deepest in the two Dakotas, is by its depth (1,483 feet) and its pressure (97 pounds) allied directly to the deep high-pressure wells of the James River Valley, which are so well developed in South Dakota. Its pressure being less than that at the Woonsocket, Mitchell, or Hitchcock wells, is referable without doubt mainly to the higher elevation of the surface. We consider it as having its water from the same source as the wells of South Dakota. It is therefore a part of the James River Basin, and what is said in the report of Prof. Culver and elsewhere on the deep wells of South Dakota will in the main be applicable to the Jamestown well and others that may be sunk in the neighborhood. We have spoken as if there were but one well at Jamestown. The well at the asylum near there has failed, apparently through some defect of the casing, or from falling of the sides. It will probably be in due time flowing better than before. The well at the city has slight variation of pressure and flow, as compared with last year. This will appear in the chief engineer's report. Whether the variation is due to causes in the tubing or in the source of supply is not certain. That it is *slight* is indicative of the general permanence of conditions.

So far, I am inclined to think this is the northern limit of the basin, but I should not be surprised if wells of some force were obtained at somewhat greater depth as far north in the James River Valley as Carrington. The tendency of opinion a year ago was to consider the Devils Lake well as in this basin. A consideration of certain facts which were collected last year, but could not be fully discussed in the limited time of that investigation, leads me now to place that well in another class, as will appear farther on. With regard to the extension of the James River artesian basin east and west, in this its northern prolongation, it is not easy to determine certainly. The probabilities will be ascertained by a careful consideration of the following facts: A deep well at Fargo, in the Red River Valley, 500 feet lower than Jamestown, failed to give any water that reached higher than the surface, and the water that came was from a much less depth. A deep well at Bismarck, on the Missouri River, failed to give flowing water. The pressure of the water at Jamestown would barely suffice to raise it in a closed pipe a little over 200 feet. The Coteau du Prairie east and the Coteau du Missouri west of the James River, on the Northern Pacific Railway, rise to considerable height above the level of the valley. Of these known facts only one is favorable to the expectation of finding artesian flows east or west of the Jamestown well from the deep-seated water-bearing stratum; that is the pressure and flow of the Jamestown well. East or west of that well, at elevations not exceeding 200 feet above it and not at any great distance, we should be warranted in expecting the drill to give artesian water at depths similar to that of Jamestown. West of Jamestown the strata lying above the water-bearing zone are probably thicker and the well-boring would have to be deeper, besides the extra depth due to increased elevation. Eastward it is probable the reverse is the case, and that the water zone would be reached at a less depth than that indicated by the increased elevation.

The profile and section along the line of the Northern Pacific Railway from Valley City to Steele will indicate this to the eye (Fig. XVII).



a, Drift. b, Upper Cretaceous Shales. c, Lower Mezozic Strata. d, Paleozoic. g, Granite.

Fig XVI. Section from the 97th meridian to the Mouse River through Rolla and the Turtle Mts. The other towns named are S. of the line.

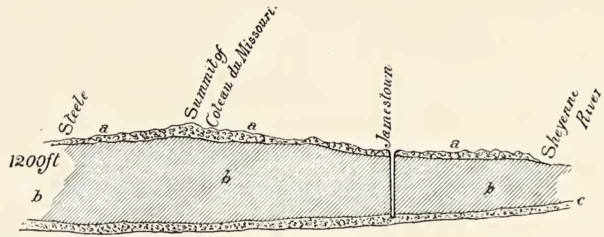


Fig XVII Section from the Cheyenne River to Steele, South of and approximately parallel with Northern Pacific Railway.

a, Drift. b, Upper Cretaceous Beds. c, Artesian Water Bed.

If experimental borings were to be made on this line, the points to consider in locating the well would be—

(1) Elevation above Jamestown.

(2) Freedom from the surface (glacial) deposits.

(3) Availability of neighboring land for irrigating purposes.

The second class of wells in North Dakota are those which have a depth of from 200 to 400 feet and a pressure of 10 to 30 pounds to the square inch. In this class are wells at Hamilton, Grafton, and at Devils Lake. These are usually spoken of as deep wells because the borings were made to depths from 900 to 1,600 feet. It was therefore assumed that their source of supply was the same as that of James River Basin. But it is a fact that the water does not come from the bottom of the wells, and that the pressure is so much less than would be expected if the source were the same. This will be understood when it is known that the elevation above sea level at Woonsocket is just over 1,300 feet and the elevation at Hamilton and Grafton a little over 800 feet. If the wells at these places were supplied from the same source the surface pressure at the lower elevations would be much the greater. The very reverse is the fact. Hamilton has a pressure of 26 pounds, Grafton of 11 pounds, and Woonsocket 147 pounds, to the square inch.

There are numerous wells in the Red River Valley with pressures ranging from less than a pound up to the pressure of Hamilton. These deeper ones seem to have their supply from a horizon or horizons below the highest of the shale beds, *i. e.*, within the Cretaceous formations, and it is probable that the shales have been cut away somewhere in the region and allowed the waters from gravels and sands of the drift which overspreads the region to reach lower beds, from which otherwise they would be absent.

The wells in the neighborhood of Grafton vary from 200 to 360 feet, and have a very nearly uniform pressure of 10 or 11 pounds. The deep city well is 917 feet deep, but the water flowing from it is from the depth given above, while the more saline supply found deeper is not used. These wells, and all the wells of the Red River Valley, including the new ones near Hillsboro, have their water from Pleistocene gravels.

This great valley is the bed of an ancient lake, known to geologists as Lake Agassiz. When the great ice sheet that overspread this part of the continent was retreating northward, the high lands of Minnesota and the Pembina Mountains with continuous higher land to the south, formed the east, south, and west shores of a sheet of water exceeding in size the present Lake Superior, whose northern boundary was the wall of ice. As the wall retreated north the level of the lake was lowered, and when the ice was nearly all gone the drainage to Hudson's Bay was established and present conditions began. The great fertility and smoothness of this Red River Valley is due to the deposit of comparatively fine sediment from this lake. These fine sediments lie over gravels and bowlders and clays which were deposited while the ice was present, and these gravels are now charged with water, which finds its way down from exposures on the shore lines of the old lake. People in the region sometimes imagine that the water in these wells derives the force which brings it to the surface from higher bodies of surface water—as the Devil Lake—or from such higher land as the Pembina Mountains. But the low pressure of the wells forbids such assumption, and only a few miles west of Grafton there is a ridge where the water barely rises to the surface. It is to that ridge itself, and to the exposures of gravel and other porous strata upon it, that we must look for the avenue by which the meteoric water reaches the subterranean

reservoir beneath the level plain of the Red River. The designation of level, while not absolutely exact, is seen to be sufficiently accurate from the following table of elevations above sea level taken from Gannet's "Dictionary of Altitudes," second edition:

	Feet.		Feet.
Fargo	905	Grafton	834
Hillsboro	901	Hamilton	831
Grand Forks	837	Neche	838
Manvel	827		

These show the slight descent of the valley to the north through a distance of 160 miles, Neche being close to the Manitoba boundary. The width of the lake is east and west across the Minnesota-Dakota State line.

The ridge before mentioned west of Grafton shows itself at a varying distance from the river all the way south to Tower City and beyond, and there is a general rise westerly till the valley of the Cheyenne is reached, and north of the great Northern Railway this valley does not exist, but there are local depressions towards the valleys of Park River and the Little Pembina, which make decided scarps on their western sides, the escarpment known as the Pembina Mountains. This escarpment has a rugged eastern front, with much timber, and looked at from the east its appearance justifies the term mountains; though, when ascended, its three benches have only a total height of 200 to 300 feet, and its top is a smooth, level prairie, with black soil in old depressions, while in places numerous glacial bowlders show through the sod. All along the escarpment, and back into the upper plain along the valleys of the Park River, the Tongue River, and the Little Pembina, there are outcrops of Cretaceous shales, so that the waters of the gravel beds are drained away, and some probably sink to lower levels in the gravels of the eastern ridge towards Hamilton and Grafton. The Pembina Mountains are clearly not the origin of phreatic waters of the Red River Valley, but the coming to the surface on their flanks of the underlying shales points out the fact that waters on the surfaces of the shales will be forced eastward, and the supply will be kept up on the edges of the valley.

The third class of wells are those of less depth than the preceding. The source of their water is without doubt the local gravel beds, which at different depths show the irregular surface of the underlying shales and the varying thickness of the gravels themselves and the clays that cover them or separate the different beds. The clays in places are continuous sheets for some distance, and elsewhere are of very limited extent. Sometimes they represent a deposit made under the glacier; elsewhere they are patches that have been torn up and transported by the glacier. These are the smaller ones.

In sinking a well the succession of sand or gravel and clay may give several water-bearing horizons, the flow from each of which, however, will rise to one level. This indicates that the impermeable strata [clays, &c.] which separate the waters are limited in area, or have breaks in them allowing the waters to flow around or through them. This is illustrated by Fig. XV, in which it is manifest that wells at *a*, *b*, and *c* will have flowing water from the same porous bed *g*, that at *a* having only one flow, while *b* and *c* will have two flows from the different depths, the pressure at the surface being practically the same. This will be true of wells so placed whether the distance between them as represented in the figures be several miles or only a few yards. This is an ideal section, but its theory fully explains the occurrence of wells with these circumstances, and it is as true of wells of Nebraska and Colorado, where the water-bearing gravel is not of glacial origin.

Small Artesian Well, South from Tower City, North Dakota.

Actual exposures sometimes give the order of formations we have here assumed, and one such is represented by an engraving in the final report of the Geological Survey of Minnesota.

The sources of the waters, then, are not far to seek. They are in the gravel ridges on the sides of the Red River Valley—the old basin of Lake Agassiz—which receive the rainfall and pass it through their porous beds to similar beds beneath the more compact silt and alluvia of the old lake bottom.

THE CHARACTER OF THE WATER.

The water of the well at Hamilton is highly saline. Water from some other wells is also more or less impregnated with salt and alkaline minerals. There are very few wells, however, whose contained minerals are sufficient in quantity to do any injury to vegetation, and in those it is believed that much of the injurious matter will be eliminated if the water were stored in a reservoir and exposed to sun and wind before being used for irrigation. It should also be remembered that some water which would injure a tender leaf will be of great benefit if applied to a root. The season of 1891 has been very favorable for the growth of crops, but it is good to find some of the owners of artesian wells are intending to be ready next year to irrigate from 5 to 20 acres from the artesian wells they own if the rain should fail.

EXTENSION OF THE AREA OF ARTESIAN WATERS IN NORTH DAKOTA.

The conditions described of the flowing wells in the Red River Valley will probably be found to exist under the bottoms of Park River and Cheyenne River valleys, as well as others that may be extensions of the ancient Lake Agassiz; but owing to probable breaches of connection in the water-bearing strata it is possible that some areas will disappoint the well-borer where surface conditions are all that can be desired.

The general appearance of most of the land in North Dakota, from the Park River to the Mouse River and from the international boundary south, is a wilderness of ridges of gravel and bowlders inclosing numerous lakes, some of great extent, as Stump Lake and Devil Lake, and more numerous old lake beds, varying in area from half an acre to several square miles. These lake beds are grassy meadows of great fertility. Some of them are but recently dried up, and are alkaline flats, of which the beach is the first part to become captured by vegetation. In many cases the first vegetation is the well-known squirrel-tail grass (*Hordeum jubatum*), and standing on a ridge of gravel overlooking some of these lake beds the beach lines can be traced for long distances by this grass.

The structure of the country may largely be described as without drainage. There are large areas between the valleys of the Red, the James, the Cheyenne, the Mouse, and the Missouri Rivers, whose drainage only flow to neighboring lakes or lake beds whence it is absorbed or evaporated before it rises high enough to overflow a river channel or other lake bed. Many small lakes have dried up since the settlement of the country, and others that formed part of connected chains have shrunk so that they no longer flow. Devil Lake has shrunk many miles in area, with a considerable depression. Stump Lake, with steeper banks, has also subsided about as much.

This form of topography is due to what geologists know as glacial

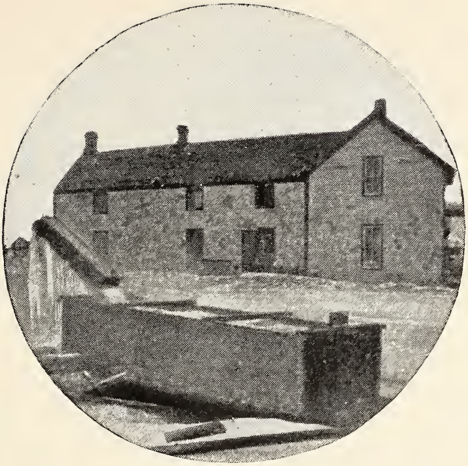
action. The whole region was covered, as a large part of Greenland is to-day, with a sheet of ice probably several hundred if not thousands of feet thick. This came from the north, and brought with it embedded in its mass great quantities of clay, sand, gravel, and bowlders, which it took up as it ground its way southward and dropped out as the ice melted with seasonal changes or left behind as the edge of the ice finally melted away and retreated to the far north. Water under the ice and water along the front of the melting ice aided in placing and modifying the deposits, and the varying action of wind, frost rain, sunshine, and vegetation have since aided in producing the forms as we see them.

There are beds of clay with bowlders and pebbles that owe their origin to the glacier, but the more prominent forms of the landscape in this part of Dakota that may be attributed to this cause are (*a*) moraines, (*b*) osars, and (*c*) kames.

Without going into details, it may roughly be stated that where great deposits of large bowlders, each more or less angular, are found together or strung out in ridges, sometimes concentric, the topography may be said to be *morainic.* Where there are more or less elongated ridges of gravel and sand, with some bowlders, the form is of the *osar* type. When, in the language of President Chamberlin, our great authority on glacial phenomena, we have "assemblages of conical hills and short, irregular ridges of discordantly stratified gravel, between which are irregular depressions and symmetrical, bowl-shaped hollows that give the whole a tumultuous and billowy aspect," we have *kames.* Besides these there are well-marked beach lines, and in some cases the *osars* have been the original shore lines of lakes.

Inhabitants of or travelers in the Turtle Mountains will at once recognize the *kame*-like forms of that region. Those familiar with North Dakota, or only passing through it on the main lines of railway, will have seen all these forms of topography. The loose materials of these formations are very absorptive of the rainfall, so that a comparatively large amount must find its way to considerable depths below the surface. These glacial deposits are from 10 to 100 feet thick. It is probable that under the surface of old lake beds artesian water may be found whose source is in the ridges of the *osars* and the *kames* that bound the lacustrine areas. To the northeast of Churchs Ferry there are wells whose water rises nearly to the surface. They are situated on the slopes of ridges which form the boundaries of the recently dried-up Lake Irvine and Lac au Morts. Besides this water that may be found beneath old lake beds and will rise in wells, there is some that would possibly justify the term underflow. This would be in limited areas, which have been in the channels of old water courses connecting present or extinct lakes. As the depth is not great to any such underflow, the "sub-canals" by which it could be made to reach the surface would not have to be long, notwithstanding the fact that the general surface of such districts is not highly inclined.

In all the region that may be called the glaciated area there are few places where water is not accessible at comparatively short distances from the surface. Where it has not artesian force it may be raised by windmills or horse power in quantities sufficient to irrigate 5 to 10 acres, or in some cases more. The irregularity of the glacial deposits makes it impossible to determine in advance what would be the result of experimental boring at any particular place, but geological investigation before such experiment would indicate with a high degree of probability where the best results might be expected.



Artesian Well at Armour, South Dakota, in Winter.

Summit of Coteau du Missouri, East of Steele, North Dakota.

What has been said previously is sufficient as to the probability of waters being obtained from wells that go deeper than the drift, but the character of the formations immediately below the drift has to do with the water supply of the drift formations. We have mentioned that beds of clay sufficient to hold down the waters of the gravels beneath are formed in the drift itself; but under nearly all the drift of Dakota the bed rock consists of the shales of the Cretaceous formations. In the Turtle Mountains and the region south of the Mouse River these shales belong to the highest Cretaceous or Laramie formations. Elsewhere they belong to older Cretaceous formations, the Montana or even the Colorado group.* But they are mostly clay shales, and so fulfill the duty of holding the percolating meteoric waters in the drift formations above. Some of them are alum shales and others gypsiferous as well as calcareous, so their presence must be reckoned upon in accounting for the minerals found in the phreatic waters of the drift region.

As the drift covers so much of the area of the two Dakotas, the precise kind of shale or other rock beneath is not easy to infer without extended observation. "How do you know these shales are here?" was a question put to the writer by an intelligent citizen of North Dakota while in the field. We will answer it here as we answered it then:

(1) The shales crop out in great thickness on the Missouri River above and below Bismarck.

(2) The shales are found with included seams of coal at Minot and in the Turtle Mountains.

(3) The shales crop out along the east front of the Pembina Mountains and in the bluffs of the Park and Little Pembina rivers.

(4) The shales—a hard, slaty kind, without fossils—crop out on the east bank and on the bottom of Stump Lake.

(5) The shales crop out in the bluffs of James River near Jamestown.

(6) At Lakota, Churchs Ferry, and numerous other places chunks (bowlders) of shale are found in digging wells.

(7) In railway cuts and stream escarpments similar chunks are found in the gravel and sand beds.

(8) The shales are reached under the lake and drift deposits in deep wells at Park River, Hamilton, Grafton, Fargo, and Northwood.

(9) The inference, then, that these Cretaceous shales underlie the whole country is reasonable.

(10) Where they (the shales) are near the surface the water in the drift gravels is forced out in the form of springs.

How far preglacial erosion has worn away the upper beds or cut into the lower ones it is not possible to say, except where there is actual exposure, or where shales from borings deeper than the drift contain fossils that would reveal the age of the formation. It is a curious fact that Cretaceous formations which in Kansas and Colorado are lithologically greatly differentiated are in the Dakotas scarcely to be distinguished in their structure from beds hundreds of feet above or below them. They are only to be distinguished by their fossils.

It is these beds of shale that have to be penetrated to reach the more porous water-bearing rocks of the James River Basin. It is these beds of shale that probably form the bottoms of lakes in the Turtle Mountains and elsewhere, as at Stump Lake. It is desirable to say a few words specially about the

TURTLE MOUNTAINS.

This region is irregularly oblong or rhomboidal in form, having its greatest length from east to west, and a sharp ascent from 100 to 400 feet above the immediately surrounding glacial plain. It rises higher to the interior. It has numerous lakes and dry lake beds from an acre to many miles in extent. Much of its surface is covered by dense forest or undergrowth. In summer most of it is absolutely impenetrable. In winter lines of travel are made over the frozen lakes. The writer has penetrated short distances into this wilderness at its southeastern edge. Also from the center of its southern boundary, near Dunseith, he has entered more than half way to the international boundary to the lower end of Willow Lake, a sheet of water several miles long, which gives rise to Willow River, which, running southwest from Dunseith, becomes tributary to the Mouse River. Here, as well as where the river enters the plain, I found the shales in position with coal. Further west I entered the mountains again and ascended Butte St. Paul, probably the highest point in the region. Its top is bare and crateriform; it rises 500 feet above the first bench of the plain, and is said to be 800 feet above the level of Lordsburg Lake, some 2 miles farther south on the plain. It is 170 feet above its immediate base on the east side, and 200 feet on the west side. From its top twelve lakes are counted, and innumerable lake beds recognized now as flat, grassy meadows. I skirted these hills along their west flank and struck through them to Fish Lake. In this part there are settlements and a passable road. But north, west, and east of Fish Lake the forest is practically impenetrable. A track has been forced through to Deloraine, in Manitoba, and the international boundary was at one time cleared of obstruction, but is now densely grown with underbrush. The writer, with a stout guide, forced his way on the boundary for 4 miles, taking three hours to do it. These excursions showed that the whole region is glacial and underlain with Laramie shales. The distinctness of every ridge, the shortness of the ridges, the depths and forms of the basins, and comparative scarcity of bowlders show that the whole topography is made of *Kames* and *Osars*, and the sharpness of outline suggests that the ice sheet lingered here till the trees were ready to grow and preserve the forms that it left. Willow Lake is 400 feet higher than the town of Dunseith. Fish Lake, which, as a translation of its Indian name, ought to be called Oak Lake, is more than 500 feet higher than Bottineau. These are large bodies of water, and this elevation suggests that these waters and those of other lakes in the mountains might be used to irrigate portions of the plain below. The engineering difficulties in the way are certainly not insurmountable, though they may be too costly.

The presence of the Cretaceous shales is announced along the south front of the mountains by the issuance of numerous springs. The principal are at—

(1) Steele's ranche.
(2) The old Dunseith brewery.
(3) The mineral spring near the outlet of Willow River.
(4) McBrayen's spring, north of Bottineau.

The first of these has a measured flow of 286 gallons per minute, which is possibly below the actual amount of water, as the minerals have formed round it a vegetable tufa that will allow some to escape unseen, especially during measurement. The tufa at well No. 2 has built up spongy wet ground all around the well, and it is scarcely possible to say where the spring is. The wet ground is several hundred

Lakes in the Coteau du Missouri Section.

feet in extent. At well No. 3 the tufa is a mound 30 feet high and more than 100 feet across. A stream escapes near the base of the truncated conical mound, but the main spring is near the top. A considerable amount oozes out also in small quantities all over the mound. The tufa is black and smells sulphurous, and the water evidently derives its minerals from the shales in the neighboring hills. The two principal flows were carefully measured. They give 42 gallons per minute. I estimate that the escape elsewhere would double the amount, and if the mound were tunneled, so that the water could flow at a lower level, it is probable that there would be 150 gallons per minute or more.

At well No. 4 the conditions preclude measurement. A spout, possibly carrying one-fourth of the water, discharged 16 gallons per minute. This water was mineralized also, but not sufficiently to injure vegetation. Neither would that at Steele's spring. The mineral spring No. 3 fosters certain kinds of vegetation. Only Steele's spring is situated favorably for irrigation. It fills a lake of several acres, more than a mile away.

VARIATION OF LAKE LEVELS.

For several years past the climate of the Dakotas has been becoming drier. It would be well worth inquiry to determine whether this is a variation that will reach a maximum and then change to the other direction, or whether it is all in one direction with slight fluctuations. It is probable that more evidence is within reach of persistent investigation, but we took such as came in our way. Let us note some of the evidences of increasing dryness from the region of Devils Lake. Capt. Herman, the owner of the steamboat on that sheet of water, built piers and other works that when built were at water level, but now are far above it. In 1883 he had the level of the lake carefully marked. Till the autumn of 1890 it had fallen 7 feet 3 inches. There is a beach also at a higher level, where the lake must have been and probably stood for several years, that, judging by rings of trees since grown, must have been sixty or seventy years ago. Stump Lake, to the east of Devils Lake has at its its eastern extremity a well-marked beach line cut in the hard shale from 3 to 5 feet above the present water line, and only a few years ago the lake was on that beach. Only five years ago Irvine Lake and Lac au Morts, to the northwest of Devils Lake, were extensive sheets of water, several feet deep. Now grasses are encroaching on their dry beds. These two lakes were connected with Devils Lake by a broad stream between 400 and 500 feet wide, which gave rise to Church Ferry, where a town, but no ferry, is now. Numerous other shallow lakes of six or eight years ago are now hay meadows, and some have been plowed. In the Turtle Mountains instead of twelve lakes fifty were formerly counted from the top of Butte, St. Paul.

The present year has been wetter. Some alkaline flats of last year are shallow lakes this year. Some lake meadows have water too deep to allow the grass to be cut. The melting of the snow raised the water of Devils Lake, according to Capt. Herman's testimony, 9 inches, and the rainfall since had kept it at that level till August, when I was there.

This is a fluctuation that may be simply seasonal, or it may be the turning-point of a number of seasons. There are two facts that seem to point out that there have been drier times than the last few years. Stump Lake is said to have derived its name from the stumps of trees, standing as they grew, in the bottom of the lake. A similar phenomenon is seen in one of the bays of Devils Lake. If these should be shown not to be caused by landslides, it would be certain in past times there

had been periods both of greater dryness as well as of greater humidity, and it may be that the recent dry years may be merely a variation in a curve of increasing humidity.

If this should prove to be the case we believe that before the great curve again persistently descends the condition, caused by settlements—the occasional irrigation, the general tillage of the surface, the proper attention to forest growth—will make the region permanently habitable.

THE UNDERFLOW.

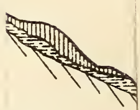
The word "underflow" is in the act of Congress which prescribes the work of this investigation. The writer and his colleagues have given attention to the underground waters of the plains region, and an examination of general results enables us to define what is properly included in the word "underflow." In those parts of this report relating to North Dakota, as well as to western Kansas, Nebraska, and eastern Colorado, the term has been used, and it will be found also in Prof. Hill's discussion on the basin regions of the Southwest, as well as in Prof. Hicks's report on Nebraska. We propose briefly to summarize the matter and indicate the right use of the term, as well as the extent of the thing itself.

That the term should be in the act of Congress indicates that those who were interested in promoting the bill represented the common Western belief to the effect that what was meant by the common use of the term exists and might be made more useful than it is at present. We have heard speakers, dilating on the advantages of the semi-arid regions, refer to "the mighty underflow of the plains." In reference to particular valleys, we have met the statement that the "underground Platte" and the "underground Arkansas" are greater streams than the visible streams that bear those names. The underflow of the latter river is spoken of sometimes as being 50 miles wide, and sometimes the subterrene waters of the plains, both valleys and uplands, have been spoken of as one great underground ocean, with a general movement to the south of east. That these terms are used by intelligent people over wide regions would indicate that there are facts that warrant at least their local application and justify an investigation as to the extent of the region or regions in which it is proper to use the term "underflow" for underground waters.

Some of the ideas of the underflow are clearly extravagant, but even these have had a basis in facts, and a not illegitimate desire to explain these facts. The most extravagant form under which we have heard the underflow defined and explained is about as follows: There are heavy snows on the Rocky Mountains and subordinate ranges; these are melted every summer. There is a large body of water supplying wells on the plains in Wyoming, Nebraska, Colorado, Kansas, and Texas. There is a general slope of the country from the northwest to the southeast. There are immense springs in a line across the State of Texas. There are springs of fresh water rising in the bottom of the Gulf of Mexico. Therefore, there is a vast body of water under the plains, moving from the mountains toward the sea, capable of irrigating the whole country, and, as one person said, "It is God Almighty's method for the redemption of the arid region."

Of the facts alleged in the above statement, most of them are as stated. The extravagance consists in connecting things in the mind

The Plains. A Dammed Draw on the Llano Estacado.



that are not connected in nature. The proper relation of these facts is shown in various parts of the report and their great actual value realized. On the other hand, some facts that are relied on as helping the doctrine of underflow as above given are shown to have no relation to it. In Prof. Hill's discussion of the geology of middle Texas it will be seen that the waters of the great Texan springs are fully accounted for without any recourse to the distant mountains. In Prof. Hicks's report it will be found that the great volume of the Loup rivers of Nebraska and of the wells on the interfluvial uplands is referred, without any possible contradiction, to the rainfall of the plains themselves. I have shown, in the general discussion of the topogragby of the plains region investigated, and Prof. Hill in considering that part known as the Llano Estacado, that the great body of the area of the plains is cut off from contact with the mountains by deep river trenches, which make it impossible for them to receive any benefit from the melting of the mountain snow. (See Fig. XII.)

But the fact remains, that under the alluvia of the great river valleys, and under the surface of the high prairies where nothing has grown but short grass or desert plants, there is water in great abundance, which, by natural or artificial means, may be put on the surface and redeem a large part of it from aridity.

Let it be understood that all rocks (this term includes clays, sands, and gravels, as well as limestone, granite, and the other consolidated materials) will hold some water in their pores as well as in fissures and cracks, but when full they will hold no more. That is, they reach a point of saturation. Water from the surface that is not evaporated gets down into the lower strata, which hold more or less according to their porosity; and, according to the character of surface strata and dryness of climate, a line of saturation is established at greater or less depths. This water escapes as springs or underground rivers (as in Kentucky Mammoth Cave), which reappear as surface streams. They are carried to the sea or evaporated. The supply from rainfall and the escape by springs implies an underground motion, a flow. This is by percolation and sometimes only capillary percolation, and must in most of its course be very slow. The estimate of velocity made by Prof. Hicks for the Loup River region, while approximately correct for these divides and others on the Republican River, is probably the highest rate of underground percolation that will be admitted by investigators. In valleys the direction of underflow may be assumed to be the same as that of the surface streams, but its rate of motion is yet a very uncertain quantity. The report of the chief engineer may be consulted on this head.

That the subterrane waters of the plains formations (and this is not to be understood of the deeper waters that supply the artesian wells of the James River Basin in the Dakotas) are cut off from mountain supplies has been already shown. An inspection of this section, and profile across Kansas on the one hundredth meridian and the shorter one on the one hundred and second, will show that there also the waters of the valleys are cut off from connection with the waters of the divides by the outcrop of the bed rock—chalk and shales. This is true farther west also, though the areas of the divides are larger there, and west of the one hundred and second they interlock. But the trenches of the great rivers, Platte and Arkansas, cut down also to bed rock; so that for the subplains waters north of the Platte and between the Plattes, and the divides between the Platte and Arkansas, there is absolutely no connection, and the plains of Texas are again separate

Fig XII. Profile from the Rocky Mts. West of Denver through the northern tier of Kansas Counties to Belleville E. of 98th meridian

Scale { 1" 887000 horizontally
1" 9600 Vertically

a. Colorado Tertiaries of the Denver Artesian basin, b. Plains marl. c. Tertiary Grit. d. Upper Cretaceous. e. Middle Cretaceous (Colorado Group)

f. Dakota g. Jura-Treas. i. Archæan

from these. That is, each region of the great plains as separated by the mountain rivers is an independent area as to the source of its subwaters. That source is in each case the rainfall of the region itself.

The water-holding bed beneath the high prairie is in each case some form of the formation we have called the Tertiary grit—the mortar beds, conglomerates, or gravels.

In the eastern Dakotas the somewhat similar post-Tertiary gravels and sands serve a similar purpose, to conserve the waters which supply the shallow wells, artesian and other, of that region.

If, then, all these facts were kept in mind, and the term underflow were used for the phreatic waters of the plains, we should not object. But, as the term has led to exaggerated ideas of its quantity and erroneous ideas as to its source, we should prefer to limit the use of the word "underflow" to the waters of the great valleys found in the alluvia under the beds of the streams, and to a limited extent under the fertile bottoms which bound the stream beds. We would speak of the underflow of the Yellowstone, the Platte, the Niobrara, the Frenchman, the Republican, the Arkansas, the Cimarron, the Canadian, and any streams in which experience had shown its presence or the structure warranted the expectation of it. The Prairie Dog, the Smoky Hill, and other plains rivers will certainly have underflow in some part of their valleys. It is also mentioned in another place that *underflow* will probably be found beneath the old channels that connected extinct or existing lakes in the glaciated areas of the two Dakotas.

With regard to the width of the underflow belt in the great valleys the following facts should be borne in mind. That it can not, on the average, exceed that of the bottom land adjoining the river, but that the underflow may be fed, as the visible streams are, by the coming in of lateral valleys, and where a large tributary valley comes in there may be a larger apparent breadth in the main valley. There are cases also where a tributary stream is lost as it enters the alluvia of the main valley. This may increase the general area of the underflow of the valley, or it may simply follow an underground bed of sand or gravel that fills what was the original channel of the affluent which is now hidden by post-Tertiary detritus. As far as the proved width of the underflow is concerned, it should be remembered that the sub-flow ditches (technically called sub-canals by the engineers of this investigation) on the Platte above Ogallala, on the Fountain, north of Pueblo, on the Arkansas, at Hartland and Dodge City, have each kept close to or under the actual beds of the streams. Wells that utilize the underflow for the supply of cities are in every case close to the beds of the streams, and this is economically correct. It is best always to act where previous experiments have demonstrated there is water, and leave further experimentation for future needs. It may here be noted that work has begun at a point near the Colorado-Kansas State line to utilize the underflow of the Smoky Hill River, and near Limon, Colo., works are under way to tap the underflow of the Big Sandy.

The existence of old river beds now filled with Tertiary or post-Tertiary gravels has been revealed in Nebraska and other localities, and these may give a supply of water from an underflow where it would not be suspected from surface conditions. On the other hand, there are places—notably in the valley of the Yellowstone and the upper Republican—where the subjacent bed rock comes near the surface and almost pinches out the underflow altogether, decreasing its width and reducing its depth. Where any large attempt is to be made to utilize the underflow, a geological examination of the immediate locality should precede the work, to detect these conditions if they exist.

We have shown above that the phreatic waters of a high divide are not connected with those of neighboring divides from which they are separated by deep river valleys, and this is made plain to the eye by the profiles in the "Progress Report" of the chief engineer in January, 1891. Yet it is true that the valley underflow as well as the visible streams are fed by the waters under the higher plains. This will appear from the fact elsewhere brought out that the rivers of the plains have their permanent water after they have cut to and into the Tertiary grit which is the holder of the phreatic waters of the high prairie. This connection is also seen in the September rise of the Loup rivers, and the October rise of the Republican, and the steady perennial flow of the Frenchman.

In estimating the volume of the underflow it is very easy to be mistaken. Loose sands and gravels will hold more water than compact sands or sandy clays. The measure of a flow in a valley is that which will pass through the more compact parts of the alluvia. The looser textures hold more, but if they are surrounded by the closer beds they will be as large reservoirs with an insufficiency of escape pipes. The data on this part of the subject supplied by the chief engineer of this investigation should be carefully studied.

In conclusion, we would repeat that it would be best to restrict the term underflow to the proved subwater of alluvial valleys and possibly to that of some of the basin regions of the Southwest. The common, well-digger's term, sheet water, may very appropriately be used for the bodies of water which are so abundant under the higher levels of the Great Plains.

ARTESIAN WELLS.

The artesian basins in the Great Plains have not been increased in number since the report of the brief investigation last summer, but important increments have been made to the areas of some of the principal.

The regions having the largest wells and the largest areas are, as was previously reported, the James River (Dakota) Basin and the Fort Worth-Waco Basin in Texas. The latter has had a great increase in the number and volume of its wells, and the report of Prof. Hill gives definite information as to the geologic source of the water and the limits beyond which water can not be expected to be obtained. The Dakota Basin has had many additional wells sunk and its area extended by the obtaining of water at Armour and Chamberlain. It was in this westerly direction that the extension was expected, the great pressure of the waters at Woonsocket, Huron, Hitchcock, and elsewhere warranting the prediction that it would be found to reach the heights of the western coteau. Examination in western South Dakota in connection with this extension warrants the expectation, elsewhere expressed, that the area of the artesian region will be extended on the west side of the Missouri toward the Black Hills, and that the name James River Basin must give way to the more extensive one of the Dakota Artesian Basin. Interesting details of the new wells and remeasurements of old wells, with an account of the irrigation experiment at Aberdeen, will be found in the report of the chief engineer. Whether the facts recorded show any falling off in the product of the wells owing to the increased number or otherwise, it will be wise to use the caution suggested by the wells at Denver and Fort Worth, not to bore the wells too close together, as no matter how large the underground reservoir may be, it can be drained by persistent tapping.

The small artesian areas in Kansas—Meade County and Hamilton County—show no falling off in the yield of water, while further examination confirms previous views as to the source of the water, viz, that it is from breaks in the surface strata admitting meteoric waters, in a region not very far to the west of the artesian wells. This is also true of the Denver Basin and other regions of limited artesian capabilities mentioned in last year's report. Statements of Prof. Hill's report suggest the possibilities of artesian water in proper localities of New Mexico and west Texas, which emphasize remarks on the failure to obtain water near Santa Fe. If that experiment were made farther down the slope it is possible that a flowing well would be obtained.

The question of the scource of the waters of the shallow wells of eastern South and North Dakota is answered, practically for both States, in the chapter on North Dakota (see *ante*), and such a description of the glacial deposits of the region is given as will enable any intelligent reader to understand the formations of that part of the country and their relation to the supply of phreatic waters.

Returning to the question of the source of supply of the artesian waters of the great Dakota Basin, we have to say that there is nothing yet learned to suggest any other origin than that given last year, viz, the outcrops of the Dakota and other sandstones on the slopes of the eastern foothills of the Rocky Mountains and subordinate ranges. The examination of the east front of the Black Hills, and of an exposure of sandstones north of the North Platte in Wyoming, and of the same formations with others east of Great Falls in Montana, all confirm the previous opinion. It is to be expected that examination of the region east of the foothills from the North Platte to the Great Falls of the Missouri would probably make the opinion absolutely certain. There has been a suggestion that the Missouri River is the source of supply, but this will be dismissed as soon as it is considered that to raise water to the height which the pressure at Woonsocket shows, the supply would have to come out of the river much farther up than Bismarck, because water will not rise higher than its source, and the elevation of Woonsocket is 1,308 feet and that at Bismarck is 1,618 feet above sea level, the pressure at Woonsocket wells being such as would raise the water 350 feet higher than the surface there. If there were leakage from the Missouri up there sufficient to support the flow of the Dakota wells, now several years old, it would be apt to show itself in some decided manner in the river bed.

We have previously observed that the wells at Coolidge, in the Arkansas Valley, have their water in the same Dakota sandstones, but that they do not get it from the mountains to the west, on the flanks of which the same sandstones are upturned. At Oberlin, in northern Kansas, a deep boring has penetrated the same beds, but without getting any supply of water that warrants the supposition of a mountain source. (It is probable that it rises not by *hydrostatic*, but by *gas pressure*, of which other examples are given below.) The explanation of this is probably found in facts which are referred to in the report of Prof. Hill. This is, that it is not in mountain uplift that we find the best sources of artesian waters, but rather in the exposure of porous strata lying at comparatively low angles of bedding, giving wide areas in which to absorb rainfall and without breaches of continuity caused by the faulting or folding of mountain structure. The upturned strata (cretaceous) on the flanks of the mountains west of Kansas and southern Nebraska dip at a high angle—sometimes quite vertically—giving small area of absorption, and probably below the surface are so flexed and broken that they can not carry far the waters they do absorb. On

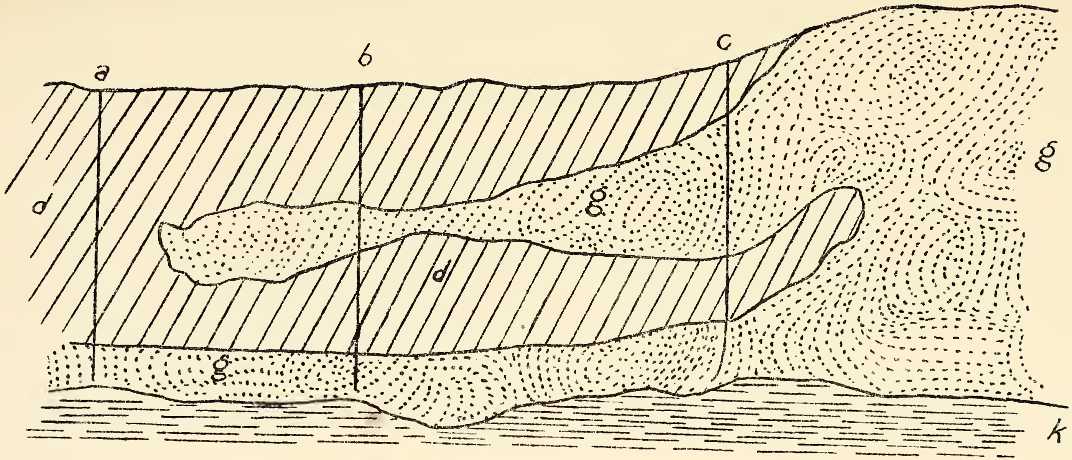


Fig. XV Showing conditions of water bearing strata in relation to other formations in the Glaciated areas. a. Well with one water level. b. c. Wells with two water levels. d. Impervious clay. g. Water bearing gravel k. Subjacent impervious shales

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Fig.XX Conditions of Artesian Wells

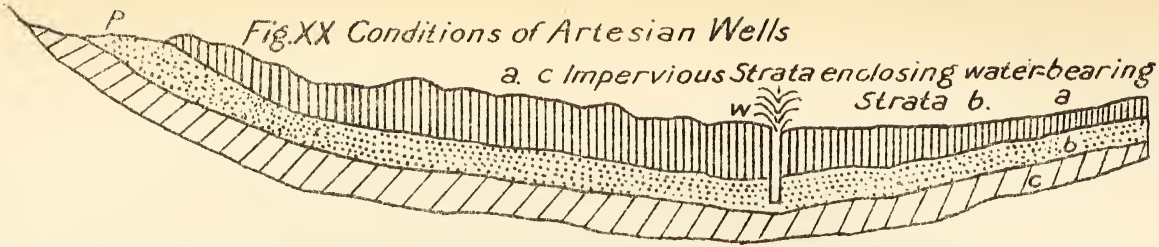
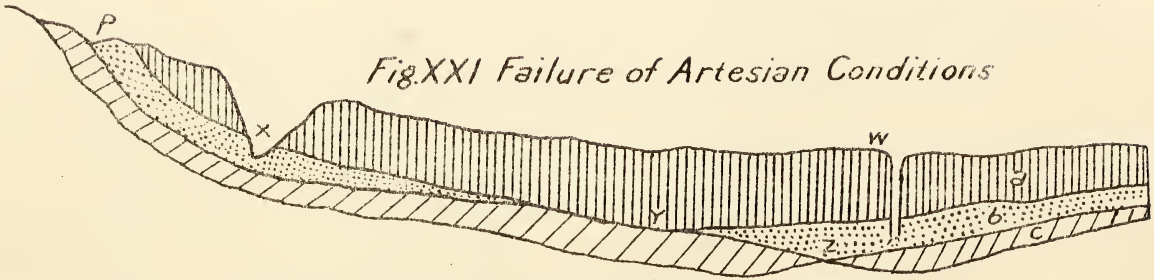


Fig.XXI Failure of Artesian Conditions



X. Breach of continuity of upper impervious beds

Y. Breach of continuity of water-bearing strata.

Z. Breach of continuity of lower impervious strata

a. b. and c. as in Fig XX

the other hand, the strata on the flanks of the Black Hills dip at comparatively low angles, while those examined in Montana and Wyoming have still more gentle slopes to the eastward. It is possible that artesian areas like that at Miles City, Mont., whose source of supply is the Laramie sandstones, may be multiplied where there are regions sufficiently large, not cut up into "bad lands" by the drainage. We would repeat the conditions that are necessary to have a flowing well, so that they be permanently within reach for reference in the semi-arid regions.

(1) The water-bearing stratum must have a continuous dip in one direction, or it may have a synclinal or double dip to form a trough or basin.

(2) It must have an impervious bed (shale or clay) below it, to prevent the water escaping to a lower level.

(3) There must be an impervious bed above the water-bearing stratum, to confine the water to the porous bed.

(4) The water-bearing stratum must be exposed to rainfall at its highest part.

(5) The surface of the land where a flowing well is expected must be lower than the exposed area of the porous stratum.

These conditions are all shown in Fig. XX, in which a well at *w* will flow with a force dependent on the difference of elevation of *p* and *w*. If the climate at *p* be very humid the last statement will be entirely correct, but if it be somewhat arid the surface point of saturation will be the level from which force will be transmitted to the artesian flow in the hollow of the basin.

There are circumstances in which the artesian conditions seem to be present when no flow rewards the labor of the well-driller. These are represented in Fig. XXI. The first is indicated at *x*, where a ravine cuts through the superior impervious beds and allows the waters of the porous stratum to escape by springs or mere oozings. Then the porous stratum itself may be pinched out as at *y*, and pinching out, or giving place to a clay shale is not uncommon in sandstone formations; or the lower impervious bed may be broken and allow escape of the waters to a lower level as at *z*. Should any one of these conditions be present there will be no flowing well at *w*, though the record of the drilling might show identical series of strata passed through as in the flowing well of Fig. XX, and the elevation might be even more favorable as compared with *p*. The breach indicated at *x* might exist, and the ravine be filled up with porous material that would carry off the springs to a great distance so that their connection with the porous strata exposed at *p* would never be known. Wells do fail where the conditions seem favorable. The failure is due to some such causes as are here indicated, but which, from the nature of the case, can not certainly be known.

The conditions as shown in Fig. XX, are almost exactly those that would be shown by a carefully made diagram of the actual levels and stratification from the Black Hills to the James River, and across the region of the Fort Worth-Waco Basin of Texas, as well as other regions of proved artesian supply.

The geologic formations which have yielded artesian water in the west were enumerated last year, thus:

The glacial drift.
The Tertiary formations.
The Laramie.
The Dakota.
The Triassic "red beds."

To this list must be added the "Trinity sands," which lie between the Dakota and the Trias, and we ought to emphasize the remark formerly made, that the combined Jura-Trias (of Montana and the Black Hills) must be regarded as auxiliary to the Dakota formation in giving area to the gathering ground and depth to the subterrane reservoir of the Dakota Basin.

Another point of note is one we have communicated to some scientific publications (Transactions Kans. Acad. Sci., Vol. XII, and Am. Geologist, Vol. V). There are flowing wells that are not artesian. We are not referring here to what have been called negative artesian wells in which there is a decided rise of the water in the tube but not reaching the surface. We refer to wells that flow from the surface, but which do not owe their flow to hydrostatic pressure, which is the cause of the flow of most wells. There is a well at Mound Valley in southeastern Kansas, and another of small flow at Lawrence in the same State where the force that lifts the water appears to be gas pressure, there being a quantity of gas sufficient to produce the result, and there being no evidence of the existence of the necessary hydrostatic conditions. Another cause also exists for flowing wells which we call rock pressure.

All rocks in the earth's crust contain some water. The more porous rocks contain the greater quantity. At a distance below the surface the superincumbent strata subject the rock masses to enormous pressure. If we assume that the rocks of a region to a depth of 1,000 feet have an average specific gravity three times as great as that of water, we are probably within bounds, although limestones and sandstones are usually somewhat less, the presence of iron in many of the beds will bring up the average considerably. On this basis a prism of the rocks to the depth of 600 feet and 1 inch square would weigh 781 pounds, which is equivalent to a pressure of 52 atmospheres. If, then, 25 feet be taken as the measure of a column of these mineralized waters equivalent to 1 atmosphere, the rock pressure would be more than the equivalent of a column of water twice this height. Let a water-bearing stratum at a depth of 600 feet, as at Richfield, Kans., be pierced by the drill we should then have the rock pressure of 52 atmospheres squeezing the water out of the rock pores, and, granting sufficient plasticity in the rock and a sufficient quantity of water, it must rise in the tube which has only the pressure of 1 atmosphere upon it. A large bore to the well and a small supply of water would be against its reaching the surface. On the other hand, a bed rock with mobile molecules at or near saturation under this enormous pressure must cause in a narrow tube a flowing well. * * * At 300 feet the rock pressure would be only half that given above, or 26 atmospheres, and the column of water to be supported will be diminished in proportion. At other depths the same proportions will hold good.

It will then be of service to persons prospecting in new regions for artesian water to be guided by all the facts at command and to make therefrom the correct inferences. Thus if a flowing well exists which has but a small volume and force, it does not follow that there is an artesian basin there. If it is a deep well it will be possible to attribute the flow to rock pressure, and in some cases to gas pressure. Let it be decided that it is one or the other, and it will be a proof that hydrostatic-pressure wells will not be found in that district at that horizon.

There is one matter that is encouraging in reference to the use of artesian water for irrigation. If the caution previously suggested is attended to with regard to the avoidance of too great proximity of wells to each other, the supply is likely to be continuous and not to vary with seasonal rainfall in the region of the outcrop of the water-bearing strata. This will be the more marked the further the wells are from that outcrop. On this we may quote the following from last year's report:

The report of Prof. Carpenter gives the records of the variations of two intermittent wells at Denver whose variability seems directly traceable to variations in rain or snow fall of the neighboring mountains. Observations on the subject of rate of flow of underground waters have recently been collated in England, but the results obtained are yet only distant approximations to verities which when accurately

known, will be of great value. It is pointed out in another report that irrigation from artesian wells or other subterranean waters will always possess a value, due to the distance of the outcrop and slowness of the percolation, which does not attach to irrigation from surface waters. It is this, that it is not likely to fail in a dry season, as the effects of the dry season will probably not be felt on the wells for one or two seasons thereafter. It is probable that in wells very distant from the outcrop of the water-bearing strata there will never be any variation due to seasonal variation of rainfall, as the character of the percolation may establish a constant, instead of variable outflow, even as the flow of blood in the veins of the body is a steady stream notwithstanding that that of the arteries is a movement of pulsations.

At the winter meeting of the Geological Society of America in 1890, Mr. J. S. Diller described a series of sandstone dikes in California. That is, dikes or walls of sandstone protruded from below—through other strata. Mr. Diller considered them due to earthquake action as far as the formation of the fissure is concerned, and the filling was by subterrane waters highly charged with sand. Dikes of this kind are new to geologic science, and a great deal of interest was attached to Mr. Diller's paper, as to a curious fact in earth history. It may be that an economic value will be attached to it almost immediately. Three of the geologists of this investigation have found similar sandstone dikes in northwestern Nebraska, near Chadron, and Prof. R. T. Hill reports the existence of one in Texas.

Many of the artesian wells of Dakota, notably at Aberdeen and Jamestown, give out large quantities of sand. If instead of the opening being made by the drill a fissure were cut in the superincumbent rocks by an earthquake, the water and sand would spout as they do now, and it would not be improbable that the fissure might in time be choked with the sand and ultimately the flow would cease. In personal conference Mr. Diller says the Californian dikes are in a region favorable to artesian conditions. The Chadron dikes and some others of which the writer has heard, in the Bad Lands of South Dakota, are between the known area of artesian waters of the main Dakota Basin and of the outcrop of the water-bearing formations in the Black Hills region. If, then, the suggestion that the existence of the dikes is connected with artesian conditions is anything more than a guess—which it may turn out to be—their existence in the region referred to is confirmatory of the suggestion already made on other grounds, that probably, artesian water will be obtained by boring in the region of the Great Sioux Reservation, between the Missouri River and the Black Hills.*

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* These dikes are described and illustrated in "Proceedings of Geological Society of America," Vol. II, by J. S. Diller, and in Vol. III, by Robert Hay.

ON THE

OCCURRENCE OF ARTESIAN AND OTHER UNDERGROUND WATERS

IN

TEXAS, EASTERN NEW MEXICO, AND INDIAN TERRITORY, WEST OF THE NINETY-SEVENTH MERIDIAN.

BY

ROBERT THOMAS HILL,
Assistant Geologist for Texas, West of 97°, the Indian Territory, and Eastern New Mexico.

CONTENTS.

ILLUSTRATIONS.

INTRODUCTION.

Dear Sir: I present herewith my special report upon the underground waters of southern Indian Territory, eastern New Mexico, and the State of Texas.

The region covered is so vast and embraces so many diverse conditions influencing the water supply that I have been able only to treat it most briefly. I feel, however, that in the accompanying pages I have at least outlined the underlying principles of the water supply and pointed out their availability.

The region assigned to the writer for investigation comprised Indian Territory (including Oklahoma), Texas, and New Mexico west of the ninety-seventh meridian and east of the Rocky Mountains, including over 300,000 square miles. This area is such a vast extent that it was impossible to traverse it thoroughly, even in a rapid manner, in the time allotted to the work. The writer, however, has fortunately spent many years in its previous study, but still feels that this report can only be considered, with the exception of the Grand Prairie region, as a preliminary outline of the water conditions.

The area has been so little studied by geographers and geologists that much time had to be devoted to tracing out and classifying its elementary geographic features as a fundamental step to the geological and economic studies dependent thereon. Even the western limit of the investigation, as defined in the organization of the work, is still problematical, for the Rocky Mountains proper cease to be a clearly defined feature south of the thirty-third degree of latitude, and are succeeded by an undefined system of unconnected mountain blocks and plains which have not yet been satisfactorily classified.

The reader of these pages should remember that the regions discussed are radically different in most natural aspects from the older inhabited portion of the United States. It is far more different from New England than is Japan. It has more points in common with Europe than with the great Mississippi Valley. The chalk lands and downs of Texas are more related to France than to the rocks of the adjacent Arkansas and Missouri States. This region of Texas, embracing nearly a third of the whole area of the artesian investigation, has more diverse geologic features than most of the remainder, which necessitates a disproportionate amount of consideration.

The writer has endeavored to give only the laws of the occurrence and distribution of water, leaving to the engineers the discussion of its utilization. Neither is it within the province of this investigation to enter into an elaborate discussion of the minute geologic structure of this immense area, but in order to comprehend its water conditions it is necessary that such features be briefly described.

I have not made this paper a statistical one, for Prof. F. E. Roessler, in his excellent report, has so completely covered that field that it would be useless to do otherwise than to refer my readers to his paper for all possible information in that line.*

I wish to return thanks to the people of the region for their kind and unstinted assistance, and above all to express my gratitude to you for the liberal manner in which you have permitted me to conduct this investigation, and hope the report will be worthy of your approval and useful to the people.

Respectfully,

ROBERT T. HILL,

Assistant Geologist for Texas, New Mexico, and Indian Territory.

Prof. ROBERT HAY,

Chief Geologist, Artesian and Underflow Investigation.

I.

THE OCCURRENCE AND AVAILABILITY OF UNDERGROUND WATER.

No substance is so universally essential and so widely distributed as water, yet the laws of its occurrence beneath the earth's surface are little studied and understood. Although everywhere desired and sought for by man to satisfy the necessities of industry, transportation, and agriculture, the art of search for it has hardly risen above guess work or the superstition of the divining rod.

Water is too abundant in the Eastern States to excite much attention, although the threatened famines of this commodity warn us that the law of its occurrence is worthy of serious scientific investigation, even in the humid region.

In the western half of the United States, however, the water question is not only serious but paramount to every other consideration, for there are vast areas as large as all New England, such as the great Llano Estacado, without a single brooklet, river, or permanent pond upon the surface, while there are other areas, aggregating one-tenth of our Union, which, together, do not possess a stream of the volume of the Mohawk or Connecticut and are utterly lacking in the accompaniments of frequent laterals and springs. Great railway lines—for example, the Southern Pacific—are obliged to haul water hundreds of miles for their engines, and have spent millions in not always judicious experiments to obtain an underground supply.

Methods for the utilization of surface waters have been developed, and it only remains to put in practice the knowledge we now possess to save and apply every particle of the available surface water of the land.

The laws of distribution and utilization of underground waters are almost as simple as those controlling surface distribution, but the popular fallacies concerning them are appalling, believed as they are by men of more than ordinary intelligence in other walks of life. The

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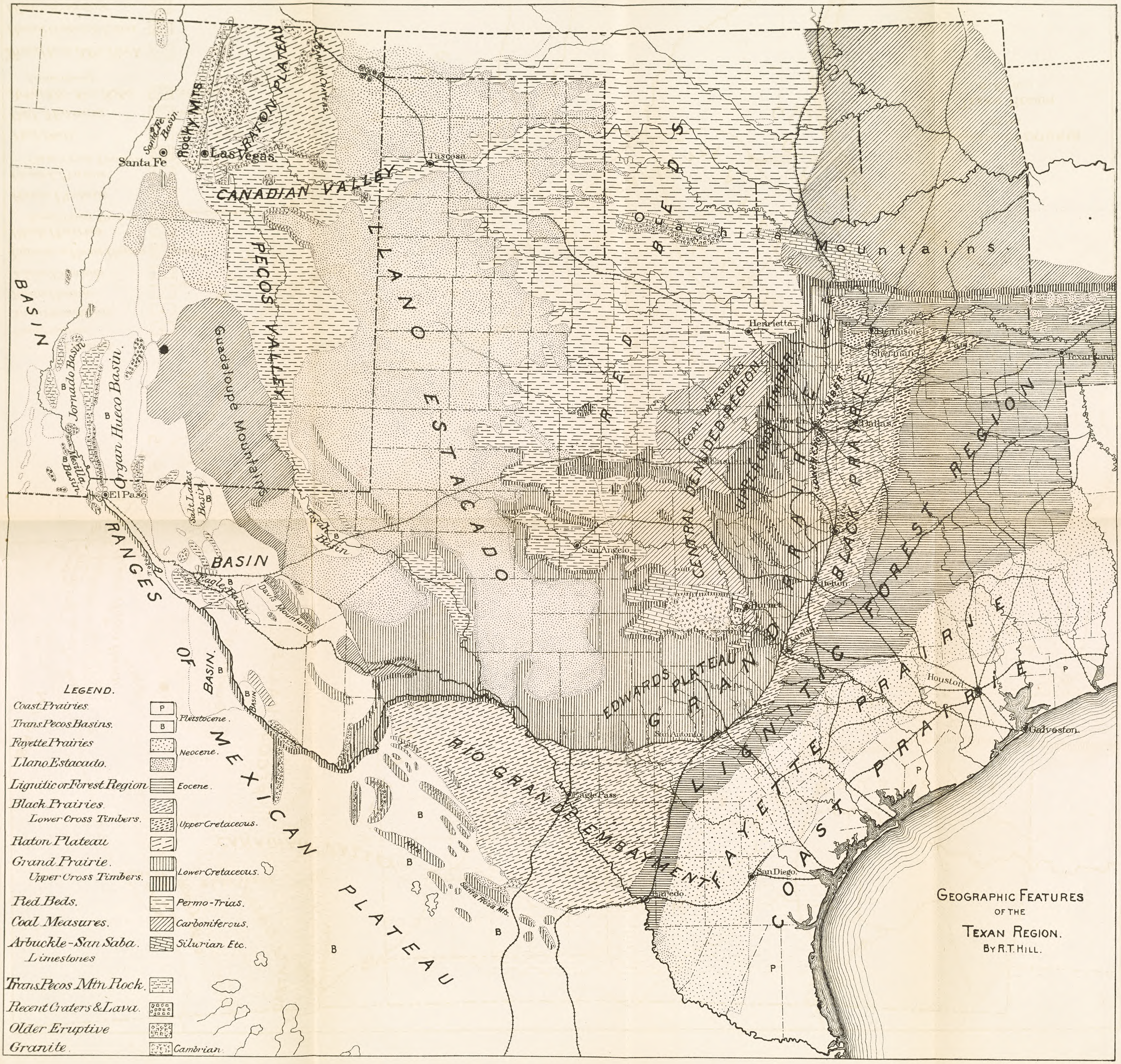
* Report on the preliminary investigation to determine the proper location of artesian wells within the area of the ninety-seventh meridian and east of the foothills of the Rocky Mountains, Fifty-first Congress, first session, Ex. Doc. No. 222.



Geographic Features of the Texan Region.
By R. T. Hill.
Legend.
Coast Prairies. P
Trans Pecos Basins. B
Pleistocene.
Fayette Prairies
Neocene.
Llano Estacado.
Lignitic or Forest Region
Eocene.
Black Prairies
Lower Cross Timbers.
Upper Cretaceous.
Raton Plateau
Grand Prairie.
Upper Cross Timbers.
Lower Cretaceous.
Red Beds.
Permo-Trias.
Coal Measures.
Carboniferous.
Arbuckle-San Saba.
Limestones
Silurian Etc.
Trans Pecos Mtn Rock.
Recent Craters & Lava.
Older Eruptive
Granite.
Cambrian.
Rocky Mts
Raton Plateau
Santa Fe
Las Vegas
Tascosa
Canadian Valley
Pecos Valley
Llano Estacado
Red Beds
Washita Mountains.
Basin
Guadalupe Mountains
Jornado Basin
Organ Hueco Basin
El Paso
Salt Lakes Basin
Ranges of Mexican Plateau
Eagle Basin
Davis Mountains
Henrietta
Denison
Sherman
Paris
Texarkana
Dallas
Coal Measures
Central Denuded Region
Upper Cross Timbers
Lower Cross Timbers
Grand Prairie
Black Prairie
Forest Region
San Angelo
Burnet
Austin
Edwards Plateau
San Antonio
Houston
Galveston
Coast Prairie
Lignitic
Fayette
Rio Grande Embayment
Eagle Pass
Laredo
San Diego
Santa Rosa Mts.

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most current of these erroneous ideas is that all underground water flows in streams "like the circulatory system of the human body," as an intelligent citizen once expressed it. The underground rivers are thought to supply every well and spring, and it is a curious sight to see the water witch or switch fakir plod over a farm with his forked stick trying to locate the "current." In the vast areas between the Rockies and the Mississippi the belief prevails that all the wells are supplied from precipitation upon the mountains, whose waters are supposed to disappear beneath the surface to rise again a thousand miles away along the coastal plain (The Galveston *News*, November 7, 1891, p. 4, top of 4th column), while beneath the vast intervening region is an inexhaustible store of water, waiting for some invention of man to bring it to the surface. This doctrine of the "underflow," as it is called, proved so contagious in Kansas a year ago that whole communities indulged in most exaggerated anticipations of its development.

In view of these facts would it not be well to examine the simple laws controlling the distribution of underground waters:

Surface waters are useful for commerce, industry, and navigation, but for agriculture underground waters are the sole dependence; even when surface water is used for irrigation it must first become earth water before it can become available for the plant roots. For this reason the farmer plows the earth's crust—to increase its capacity to imbibe and transmit water—or drains his field to remove a surplus of moisture.

The source of all underground water is the rainfall, but with few exceptions the underground supply in any region is not proportionate to its rainfall. Of the rain which falls upon the earth's surface, part is evaporated or quickly drained to the sea; the remainder is absorbed by the soil and other rocks.

All the materials composing that portion of the earth's structure visible to human inspection, inappropriately known as the crust, are more or less saturated with water. In arid regions or in times of drouth this may not be apparent or at the immediate surface where the moisture is dried by evaporation, but a fresh excavation—a post hole, a plow furrow, a blast in a quarry, or a newly dug well—will reveal the contained moisture of the earth's crust.

This moisture or earth water may be scarcely visible or may occur in great abundance according to the compactness or porosity of the rocks, the number of fissures, joints, and crevices, and their topographic situation.

If rainfall be long continued the portion of the crust upon which it falls becomes completely saturated. Upon cessation of the rainfall evaporation or drying begins at the surface, thus causing the line of visible moisture to become deeper and deeper. The line of visible moisture is known as the line of saturation or earth water, and its depth in any area decreases with the rainfall and increases with evaporation (temperature and wind movement).

Thus it is that in the eastern part of the United States, where rainfall is excessive and evaporation slow, the line of saturation is usually near the surface, while in the arid regions, like the Llano Estacado and the great basins, it is often several hundred feet below the surface.

Although the belt or portion of the earth's crust between the surface and the line of saturation may be apparently dry, evaporation is constantly going on, the soil serving, like the wick of a lamp, as a medium of capillary attraction, by which vast amounts of moisture are conducted to the surface and evaporated.

The percentage of the water of the earth's crust that escapes by evaporation is not definitely determined, but, owing to the surface exposed, it must far exceed the amount escaping by all other methods. The water evaporation is of no direct application to man and is not further considered here.

If the earth's surface were of uniform porosity, temperature, and composition the water it contained would be uniformly distributed through it, as is the water in a well-soaked sponge.

This is not the case, however, for the outer portion of our globe is composed of rocks of much greater porosity and less density than the interior, while the downward percolation of surface water can extend but a short distance, because it encounters the superheated matter of the earth's interior and is either forced back towards the surface as steam (as in the case of geysers and volcanoes) or enters into mineral combinations. Hence we must conclude that the earth water is confined to that portion of the earth's crust between the lines of heated interior and surface evaporation.

Even in this narrow belt the distribution of water is very irregular, for in places, as on the Llano Estacado, holes 300 feet deep can be drilled through soil and rock as dry as powder without reaching water, while in New Orleans water is so near the surface that graves can not be dug for the dead.

The unequal distribution of water in the saturated portion of the earth's crust is due to the difference in porous texture of the different rocks which compose it, their arrangement relative to one another, the amount of rainfall and surface evaporation and the relative altitude above or below the adjacent drainage level.

All rocks imbibe water in proportion varying with their physical structure, a fact which can be demonstrated experimentally by saturating familiar types of rock, sand, brick, chalk, glass, marble, and granite. The glass is similar in water capacity to large areas of volcanic and other igneous rocks, and will absorb no perceptible amount of moisture; marble will drink in a slight quantity; the chalk, sand, and brick will absorb nearly their own weight of water.

The manner in which rocks imbibe water is simple. In most rocks, however compact to the eye, there exists interstices, cavities, and other spaces between the minute particles which compose the mass, in which water may enter and be stored. This is especially true of all sedimentary rocks, which compose ninety-nine one-hundredths of the earth's crust. A fine sandstone, whose grains and intervening spaces may be indistinguishable to the eye, when placed under a microscope resembles a load of cobblestones, in which the spaces occupy as much of the aggregate mass as the solid stones themselves. Into a gallon measure of dry pebbles, varying in size from an egg to a pin head, may be poured half a gallon of water.

Crystalline rocks, as a rule, are more compact and less adapted for the storage and passage of water than sedimentary rocks. Nearly all the minerals which compose them are impervious, as is readily seen in a large crystal of quartz, feldspar, mica, and others. Hence, if a rock is composed of closely woven crystals of massive rocks—quartzite, granite, basalt, lava—its water receiving and transmitting power is minimum. But nearly all sedimentary rocks are composed of minute fragments of other rocks, which have been broken, transported, and arranged by the water according to their size. Most of these fragments are minute crystals or pieces of crystals, and therefore the water conditions of the rock depend upon the size and abundance of spaces between its particles rather than upon its composition.

The different capacities of rocks for holding water have been tabulated by M. De Lerse, of France, and others.

[Proportions of water absorbed by 100 parts stone.]

Great oölite, Bath	31.20
Sandstone, pure quartzose	29.00
Chalk of upper horizon, pure	24 10
Calcareous freestone	18.03
Sandstone (Gres de Beauchamp)	13.15
Sandstone, impure	4.37
Coal shale	2,85
Porphyritic trachyte	3.70
Basalt	0.83
Siberian slate	0.19
Granite (fine grained)	0.12
Hornblendic granite	0.06

Rocks which have imbibed all the moisture they can contain are in a condition of saturation, and all water in excess of this amount will pass off by aid of gravity, capillary attraction, or evaporation. The excess of water in rocks above the water of saturation is available as the source of springs, wells, and artesian supply.

If experiments with these materials are continued, each rock will be found to possess a different capacity for the transmission of the water which it has imbibed, and the capacity for transmission is entirely distinct from its capacity for imbibition. If the component particles—for instance, the quartz pebbles of a loose conglomerate or the grains of a sandstone—present a smooth impervious surface, water will cohere to the individual surfaces until the entire particle is enveloped in a coat of water. If the interstices are smaller than the average drop of water the resistance of cohesion to the free transmission of water will be greater; hence a chalk or a fine-grained brick will drink in much water but transmit little, while water will pass freely through coarse gravel. Capacity for transmission in variously grained rocks and the accompanying cohesion is similar to that seen in passing water through sieves of different mesh. Thus some chalks with exactly the same capacity for imbibition as sandstones transmit water six hundred times slower.

These materials with radically different capacities for imbibition and transmission of water have been sorted into definite sheets or strata by the water which deposited most of them, so that another important factor in the question of underground water is introduced, the stratification or arrangement of the rocks relative to one another. Earth water percolates downward through a porous stratum until an impervious one is reached (Figs. 1 and 5), while an impervious stratum at the surface will prevent the saturation of a pervious one below.

Stratification performs the important function of controlling the distribution of earth water, of resistance, transmission, and storage.

If the rock stratum is pervious and horizontal it will simply serve as a sponge to hold whatever water it receives until distributed by evaporation or seepage, unless the supply is constantly renewed by rainfall. (See Pl. I, Fig. 1.)

If an impervious sheet is above an outcropping porous stratum it opposes the tendency of water to rise by hydrostatic pressure, and if below, it opposes the force of gravity by preventing the water from percolating to greater depths. If vertical enough from faulting or folding, the strata cut off the horizontal transmission of underground water.

If strata are inclined, water is transmitted by gravity in the direction of inclination, *i. e.*, with the dip; and if the topographic conditions are

favorable flowing wells can be obtained at points more or less distant from the outcrop. (See Fig. 2.)

If the strata incline in a direction opposite to the general slope of the country, no matter how favorable the conditions may be, they will furnish no flowing artesian supply, for water can not rise above the height of the receiving area. (Fig. 3.)

If strata are excessively inclined, as in most mountain regions, artesian wells are improbable, if not impossible, over any wide area. In folded, mountainous regions the strata will soon dip below all available boring; hence the generally accepted idea that artesian wells are peculiar to regions of great stratigraphic disturbance is fallacious, except when the condition exists as in Fig. 4. A dip of 1 per cent is hardly visible to the eye, but it will carry a stratum downward 52.8 feet per mile, or 528 feet in 10 miles. A dip of 10 per cent, which is hardly noticeable, will carry a stratum 528 feet in a mile, or 5,280 feet in 10 miles. A dip of 45 degrees will carry a stratum deeper in a mile than any drill has yet penetrated.

It may now be said that the most favorable and usual condition for artesian wells is that of strata inclined slightly at an almost imperceptible angle with the surface slope. This condition prevails in gently sloping basins and not in mountains.

Theoretically, this arrangement affords a large exposure of the receiving stratum for the imbibition of water and underlies an extensive area in which wells can be obtained. All the great artesian well areas of the United States are of this type, that of the Atlantic Gulf coast of Dakota, and of Texas.

The receiving area of an artesian system is the area of outcrop of the water-bearing stratum. Its extent is proportionate to the thickness and inclination of the stratum, and its value for receiving and transmitting water depends upon the area of its outcrop and its porosity. The outcrop may be of any topographic form, but is usually in a valley of stratification which is topographically higher than the outcrop, as in the artesian areas of Texas (See Fig. 1), New Jersey, and elsewhere.

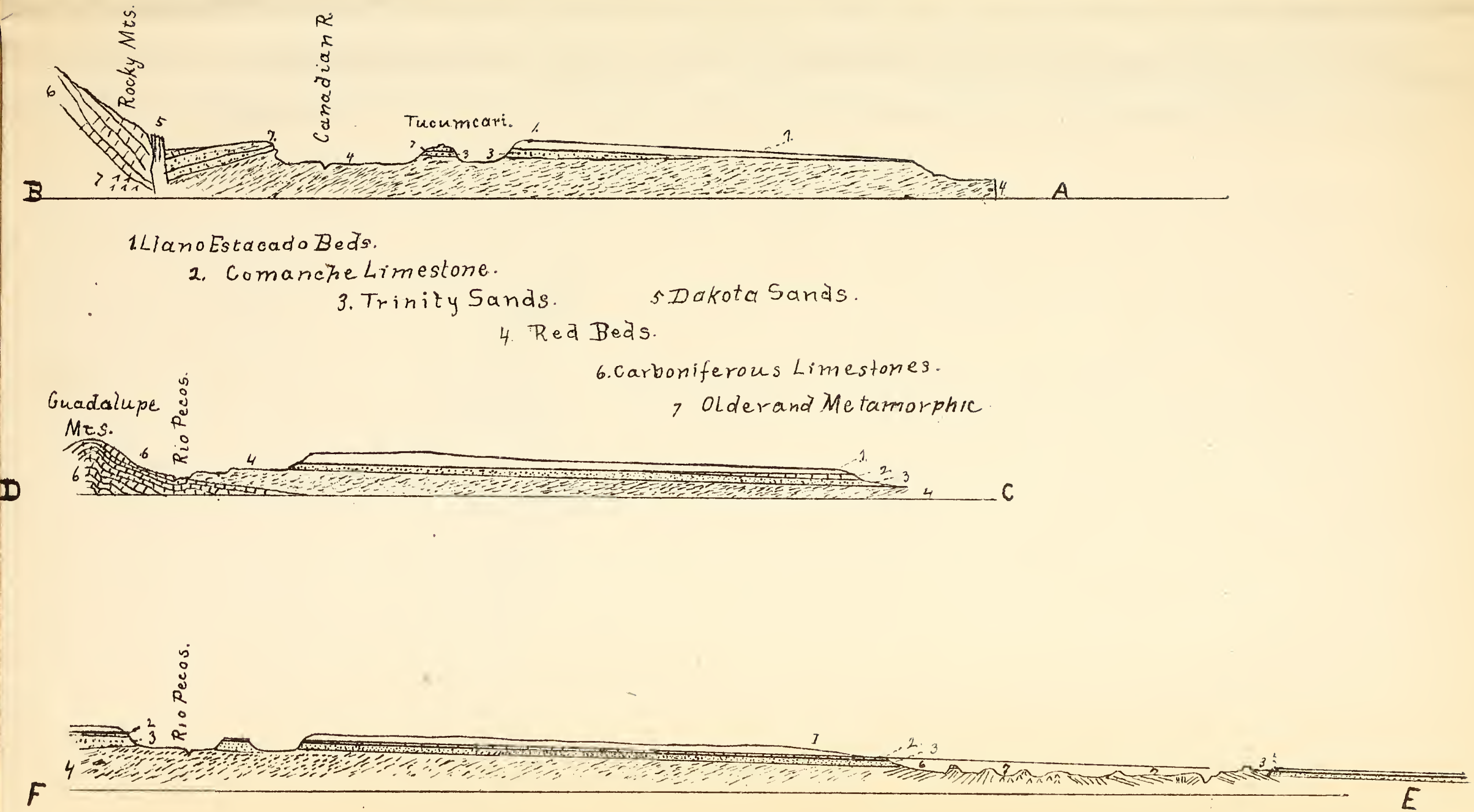
Most sedimentary rocks occur in definite succession, *i. e.* sands overlaid by clays, and by these limestones, representing the deposits laid down at shore, in shallow water and at the nearer shore or moderate depths, respectively; hence when a well is begun in rocks of the limestone group a great volume of water must not be expected until several strata of clays are passed through and the basal sands penetrated.

This sequence or triple succession is not always present, for often the upper limestones and clays have been removed, but the lower members may usually be expected, for it is very exceptional that a clay or chalky limestone is deposited unless preceded by sand.

INFLUENCE OF TOPOGRAPHY UPON DISTRIBUTION OF EARTH WATER.

If the surface were a dead level not grooved by river drainage, and were a homogeneous mass, earth water would sink to the line of complete saturation, which would be at a uniform depth, as it is in a flat, undrained field.

But the earth's surface is broken into mountains and plains and the plains are scored by valleys, just as the farmer's flat field is marked by drainage ditches; therefore, through the percolation caused by gravity the line of saturation sinks towards the level of the lowest adjacent drainage valley whose streams are usually fed by the water of saturation escaping at their level. (See Fig. 7.)


Rocky Mts.
Canadian R.
Tucumcari.
B
A
1. Llano Estacado Beds.
2. Comanche Limestone.
3. Trinity Sands.
4. Red Beds.
5 Dakota Sands.
6. Carboniferous Limestones.
7 Older and Metamorphic
Guadalupe Mts.
Rio Pecos.
D
C
Rio Pecos.
F
E

S Ex 41 ---- 52 1

GEOLOGICAL SECTION & PROFILE
FROM
SEA LEVEL AT NEW ORLEANS, LA.
TO THE
ROCKY MOUNTAINS
LAS VEGAS, NEW MEXICO.

By Robt. T. Hill.

OF

LE

S

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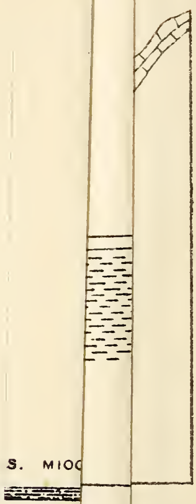

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There are two kinds of valleys in the West—stream valleys and basin valleys. The former are the product of erosion through the rock mass, caused by running streams seeking base level; the latter are the filled-in depressions of vast intermountain areas, like Salt Lake Valley of Utah. The stream valleys reduce the line of saturation of the adjacent regions to their level and carry the earth water to the sea. Basin valleys store the surface water of the adjacent mountains by imbibing and retaining it in their loose, porous strata. (See Fig. 6.)

Topographic irregularities have important bearing upon the success or failure of artesian wells, but not as great an influence as is popularly supposed, for the receiving area of artesian districts is more often a level or valley of stratification than a protuberance.

In mountains of disturbed strata, not horizontal, water level is reduced toward that of the surrounding plain.

Mountains, in general, owe their existence to the compactness and imperviousness of their structure, conditions which render them of secondary importance in a discussion of underground water, since they are quickly drained of their rainfall, except that which becomes crevice water or is retarded by vegetation.

Impervious mountains are often important in concentrating the drainage of a large area upon the porous surface of a basin-shaped plain occupying their center (Fig. 6); they actually double the efficiency of the rainfall for the basins; this fact is of especial value in the southwest, where the country is of impervious mountain and porous basin structure.

In the case of buttes and mesas, which usually consist of horizontal strata, the line of saturation is reduced by gravity towards that of the plain or valley which surrounds them (Fig. 6).

As a rule, the degree of consolidation of an impervious stratum has little bearing upon its function in artesian wells, soft clay shale is practically as impervious as a hard slate; hence the incorrectness of the popular idea in the West that a hard rock must overcap the water-bearing stratum. Consolidation, however, does decrease the transmitting capacity of pervious strata, since this power is produced by pressure which decreases the interstitial spaces of the rocks, or by mineral cement which fills the pores; hence, most of the great water-bearing areas are composed either of loosely cemented or unconsolidated sand.

WATER CONDITIONS MOST FAVORABLE IN THE NEWER (NEO ZOIC) FORMATIONS.

The older formations of the earth are more consolidated, metamorphosed, and disturbed than the newer, and hence they occur in but few places in the continuous sheets necessary to great artesian development. The newer rocks (post-Carboniferous) are less consolidated, less disturbed, less metamorphosed, less broken, and therefore are better adapted for imbibition, percolation, and transmission of water. Thus it is that with a few exceptions, the great artesian areas of the world are in the Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary rock sheets, which, as will be shown, play an important part in the region under discussion.

A section from the Gulf coast to the Rocky Mountains, say from New Orleans to Las Vegas, will illustrate the principles I have endeavored to explain (see Profile No. 3). From the coast to the ninety-seventh meridian is a large series of porous sheets of strata inclining with the

surface at only a slightly greater angle. This represents, with one or two exceptions, the condition of the entire Atlantic seaboard. These strata constitute the rocks from latest Jurassic to present time and represent a series of ancient coastal deposition plains; nearly everywhere throughout their extent artesian wells are obtained from New Jersey to Texas.

This series rests upon another of older rocks which incline to the westward and against the topograpic slope and outcrops between the ninety-eighth and one hundred and first meridian. No successful artesian wells of large volume have been or are likely to be obtained in this region. A similar negative condition exists in that portion of northeastern New Mexico which I have termed the Las Vegas shoulder; experimental wells of great depth have been drilled without success at Trinidad and Las Vegas.

The principle that greatly disturbed or mountainous areas are not favorable artesian areas is illustrated in the dip of the strata of the Rocky Mountain front, south of the Arkansas, the excessive angle of which almost immediately carries them beyond the reach of man.

The influence of structure and imbibition is shown in the basin plains. (See Fig. 6.) These vast stretches of land in the arid region have been looked upon by the professional geologist as unworthy of experimentation for artesian water, owing to the absence of consolidated strata and the prevailing fallacious idea that the "upturned edges of the adjacent mountain regions were the receiving area of all underground water." Although unconsolidated, the rocks of the basin plains are alternations of porous and impervious beds and hence are valuable artesian areas; by experimentation in boring in properly selected sites considerable water may be obtained. Non-flowing wells have been secured in many of the most unpromising plains, even in Death's Valley; as furnishing water for stock, these wells are very important.

The geological age of strata is of secondary importance in determining the occurrence of underground water, although it is a remarkable fact that with two exceptions the underground waters of our country are obtained from the Neozoic or later formations and from these only where they occur in gently sloping plains or basins, and not as upturned mountain rock.

From these fundamental principles of the occurrence of underground water it is seen that the whole question of distribution is primarily a geological one, and hence a properly constructed geological map would illustrate the underground distribution of water. For instance, a good strata map of the country would show the relative capacity of different subareas for imbibition.

This would be practicable on an extensive scale in the West, especially in the Texas region of the United States, where the formations have great areal development. Approximately the same amount of rain falls upon a great diversity of country, some of which contains great stores of water while others are entirely lacking in this essential. For instance, the mountains of the Trans-Pecos region are mostly composed of hard, impervious rocks—compact limestones, quartzites, and eruptive rocks. Less than 1 per cent of the rain falling upon these rocks is absorbed, except such as finds its way into the structure by cracks and fissures or along lines of contact. As a result of this condition, the water, after every shower, quickly flows down the slopes to the extensive flats which occupy the valleys between the mountain ranges. These flats (see Fig. 6), as well as the entire surface of the Llano Estacado, have a structure entirely different from the adjacent mountains

and are for the most part, composed of loose, porous sands and gravels so that every drop of rain that touches their surface is immediately absorbed and does not flow off in streams. This explains the utter absence of running water on the surface of these flats and its abundance stored in the structure beneath. Not only does this basin and plain formation (see Figs. 1 and 6), imbibe all the rain which falls upon its surface, but the great torrents which pour down the mountain sides and cañons disappear immediately upon reaching the plain, being imbibed by its porous structure. The constant streams, also, which flow from the snow-clad peaks or mountain springs, such as the Seven Rivers, the Tularosa, and the numerous lost rivers of New Mexico and Texas, quickly disappear upon reaching the plain.

Immediately underlying the porous beds of the Llano Estacado, which is the latest and capping formation of the area, is an impervious formation consisting of red clays called the Red Beds (Fig. 1). These constitute the surface of a large area of country east of the Llano in Texas, known as the Concho-Abilene country. This formation does not imbibe water freely like the Llano Estacado. Consequently its waters drain off rapidly and its surface is eroded with many dry creek beds or arroyos which contain running water. The rainfall upon these clays quickly flows away to the rivers and from the rivers to the sea, so that the people of eastern Texas often see great rises, usually disastrous overflows, of the red waters which quickly follow rainfall in the Abilene-Concho country.

Again, to the eastward there is a vast area of country known as the Black Prairie and Grand Prairie regions. These are underlaid by chalks, chalky clays, oölites, and chalky marls. All these formations, except the clays, are nearly as porous as sand and imbibe nearly as much water. This region, too, drinks in much of the rainfall, but not as much as the Llano.

If it were possible to view this region of mountains, Llano Estacado, Red Beds, chalks, and sands while a rain was falling uniformly over the whole region, the following diverse phenomena would be seen: First, torrents pouring down the impervious mountain sides to the plains and there disappearing beneath the level surface; second, the level surface of the Llano, void of streams or surface drainage, immediately absorbing the water or temporarily collecting it on the surface in lakes, like liquids in a chemist's filter, until it can pass downward; the impervious Red Bed plains, like the mountains, covered with rills, rivulets, and torrents laden with sediment, which soon flow into the arterial drainage of the Red, the Brazos, or the Colorado. The rainfall upon the chalky regions and the oölites is imbibed almost as quickly as upon the Llano, except in the clay areas.

After the rain ceased an observer would be impressed by the fact that the representative rocks of the different areas exhibited capacities different not only for imbibing water, but also for transmitting it through their structure by percolation, and those rocks which imbibe the least water, like the limestones, porphyries, and quartzites of the Organ, the Guadaloupe, and other trans-Pecos mountains, most slowly transmitted it, so that for days, perhaps months, springs and seeps flow from the crevices and contact plains of the high mountain slopes, keeping alive delicate ferns and rare plants. On the surface of the Llano, except where slight quantities of clay are mixed with sandy loam, in an hour or two there remains little evidence in the dry surface that a shower has fallen, the water having quickly penetrated to depths beneath. The chalks, the oölites, the marls, and the sand exhibit similar phenom-

ena with slight variations. The red beds and clay areas, such as the Black Waxy and Abilene countries, which have much clay in their structures, although imbibing much less water than the other regions, are wet and moldy for many days, according to the amount of clay they contain.

These great differences are due to the different degrees of porosity or percolation of which the rocks are capable.

In conclusion, it is well to consider the application of these principles to obtain underground water in the vast arid regions of the United States and Mexico. First, it is apparent that the best conditions for securing underground water are not in consolidated or mountain rocks, as shown by the futile experiments of the Government well borings under Capt. Pope in 1858 and the numerous failures of the Southern Pacific Road—all of which were drilled with the idea that the earth water came from the mountains. But, on the other hand, the most sterile sandy upland plains, like the great Jornado Muerto, or filled-in river valleys, like that of the Rio Grande, are the most favorable locations for imbibition and storage of underground water.

By taking advantage of this law hundreds of wells, nonflowing it is true, have been obtained upon the greatest of our supposed waterless plains, such as the Llano Estacado and the Franklin-Hueco basin north of El Paso.

The artesian wells throughout the arid regions also demonstrate this principle—especially the wells of the great basin—plains of Utah, Colorado, and California.

The supply of underground water is sufficient to reclaim for agriculture by irrigation only a very small fraction of our desert lands. Yet, by applying these principles, thousands of wells can be obtained upon areas now absolutely waterless, which would be of great value to overland commerce and to herders, and would save large amounts of money now wasted in unprofitable experiments.

II.

GENERAL OUTLINE OF THE TEXAS-NEW MEXICO REGION.

The areas treated in this paper are so vast and differentiated that it is possible only briefly to define them, including as they do portions of most of the conspicuous topographic features of our country accompanied by their diversities of climate, geologic structure, and cultural possibilities. (See Pl. II.)

Topographically the whole region consists of a series of extensive elongated parallel dip plains and plateaus (see Profile 3), extending approximately in a north and south direction, and abruptly terminating at each end by a great mountain system, extending at right angles to them—an arrangement comparable to a wide stairway, in which the steps are represented by the plains and the walls by the inclosing mountains.

This analogy can not be carried too far, however, because great irregularities and depressions will be found in the width and trend of the steps, and the structure of the two mountain systems which represent the inclosing walls is of two entirely different types and periods of architecture; moreover, the escarpments of the steps in most cases face

westward or upstairs, while the plains successively dip beneath each other. The wear and tear of time has scarred and disfigured the region, leaving depressions where the drainage or other erosion has crossed the plains and worn the mountain walls.

I have previously shown* the most salient features to consist of the following subdivisions, whose details will be discussed in the succeeding chapters:

1. *The eastern division.*—A series of present and ancient coast deposition plains, consisting of strata of Trinity and later age, cover the eastern half of the State, and collectively form what I call the coastward incline. This includes the coast prairies, the Washington prairies, the eo-lignitic or forest region, the Black prairie, the Grand prairie, and the two cross-timbers. The Llano Estacado may be generally classified with this region, but for the present I prefer to treat it separately. This division includes a great variety of surface aspects, and occupies the eastern third of the State of Texas. This can be shown by a line drawn through Montague, Millsap, Stephenville, Comanche, Lampasas, Burnet, and Del Rio. Its total area is about 172,800 square miles. The eastern half of this division is essentially similar to the adjacent lowlands of the Gulf States. The western subdivision or Black and Grand prairies are uniquely Texan and are the chalk region of the United States.

2. The central denuded region, founded upon the great Paleozoic and early Mesozoic (red beds) rock sheets which dip westward, rest unconformably beneath the group of the coastward incline and are exposed by the removal of the latter by erosion or by being upturned in the two great mountain systems which limit the region—the Ouachita on the north and the basin ranges of the trans-Pecos country and northern Mexico on the west. This division is between the eastern division and the great Llano Estacado, and may be classified into three principal subdivisions: (*a*). The country of the Coal Measures, underlaid by the peculiar sands, clays, and limestones of the Carboniferous system of rocks. It includes nearly all the eastern half of the Indian Territory, except along the Red River border, and much of the counties of Jack, Young, Palo, Pinto, Montague, Stephens, Shackelford, Eastland, Erath, Brown, Parker, Coleman, McCulloch, and San Saba. (*b*). The Burnet-Mason country, consisting mostly of granite and metamorphic rocks and older limestones. (*c*). The red bed region, including the peculiar red lands of the Concho, Abilene, Wichita, and Oklahoma regions.

3. *The mountain systems.*—(1) The Ouachita system of Arkansas and Indian Territory is older than the plains of the coastal system, which were laid down against it, and separates the Texas region from the Kansas. (2) The Basin Mountains, west of the Pecos and south of the Rocky Mountains proper (which end near Santa Fe), are composed of the uplifted, folded, and crumpled southward edges of the earlier of these plains, *i. e.*, those found on rocks of Cretaceous age. The Rocky Mountains proper form the northwestern limit of the region and are not discussed in this paper.

4. *Remnental plains of later or allied age to the Rocky Mountain uplift.*—These surround the southern and eastern border and may be

* The writer has made preliminary definitions of this region in three earlier papers: 1. "The Neozoic Geology of Southwest Arkansas," vol. 2, First Annual Report of State Geologist of Arkansas. Little Rock, 1888. 2. "Classification and Origin of the Chief Geographic Features of the Texas Region," American Geologist, Jan. and Feb., 1890. 3. Bulletin 45, U. S. Geological Survey. "Present Condition of Geologic Knowledge of Texas."

classified as the eastern continuation of the plateau region of the West. They include the Llano Estacado and the Raton Las Vegas plateau and were once continuous with the eastern division, but have been separated by the great denudation which laid bare the central denuded region. These plains occupy 91,200 square miles of northwest Texas and New Mexico.

5. Basin Plains lie between the mountain blocks of the Trans-Pecos region and are continuous in genesis and every physical aspect with the Great Basin region of Utah and Nevada and the so-called High Plateau of Mexico. The Pecos and Lower Rio Grande, from Santa Fe, N. Mex., to Brownsville, Tex., marks approximately the eastern border of this great division. The country from Idaho to Tehuantepec is essentially Mexican in physical aspects.

Each of these five grand divisions has its own peculiar features of topography, climate, geologic structure, and water conditions.

III.

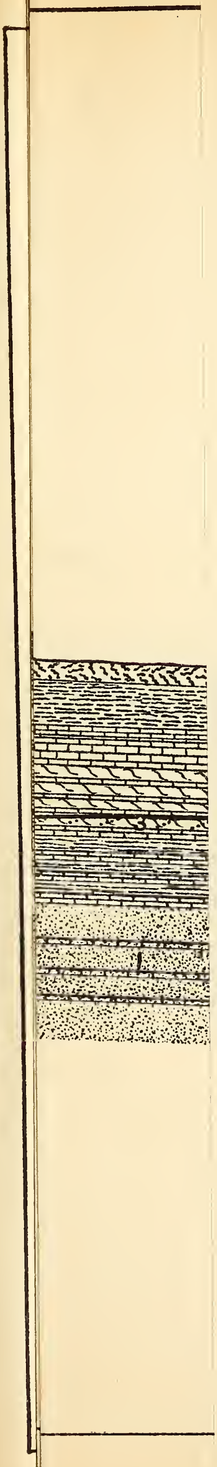
THE ARTESIAN CONDITIONS AND STRUCTURE OF THE EASTERN DIVISION, OR THE COASTWARD INCLINE.

The half of Texas east of a line drawn irregularly from the western edge of Cooke County southward to the southeastern corner of Burnet County, and from there westward to the Trans-Pecos Mountains, presents a remarkably simple arrangement of its stratified rocks, so that its artesian conditions can be easily determined. This vast area embraces a great diversity of country and of accompanying economic conditions. It also has every diversity of climate, from aridity at its southwestern corner to abundant and even excessive rainfall to the eastward. In fact, its only common feature is the favorable inclination of its various strata—sands, chalks, clays, etc.—a most important feature in water conditions.

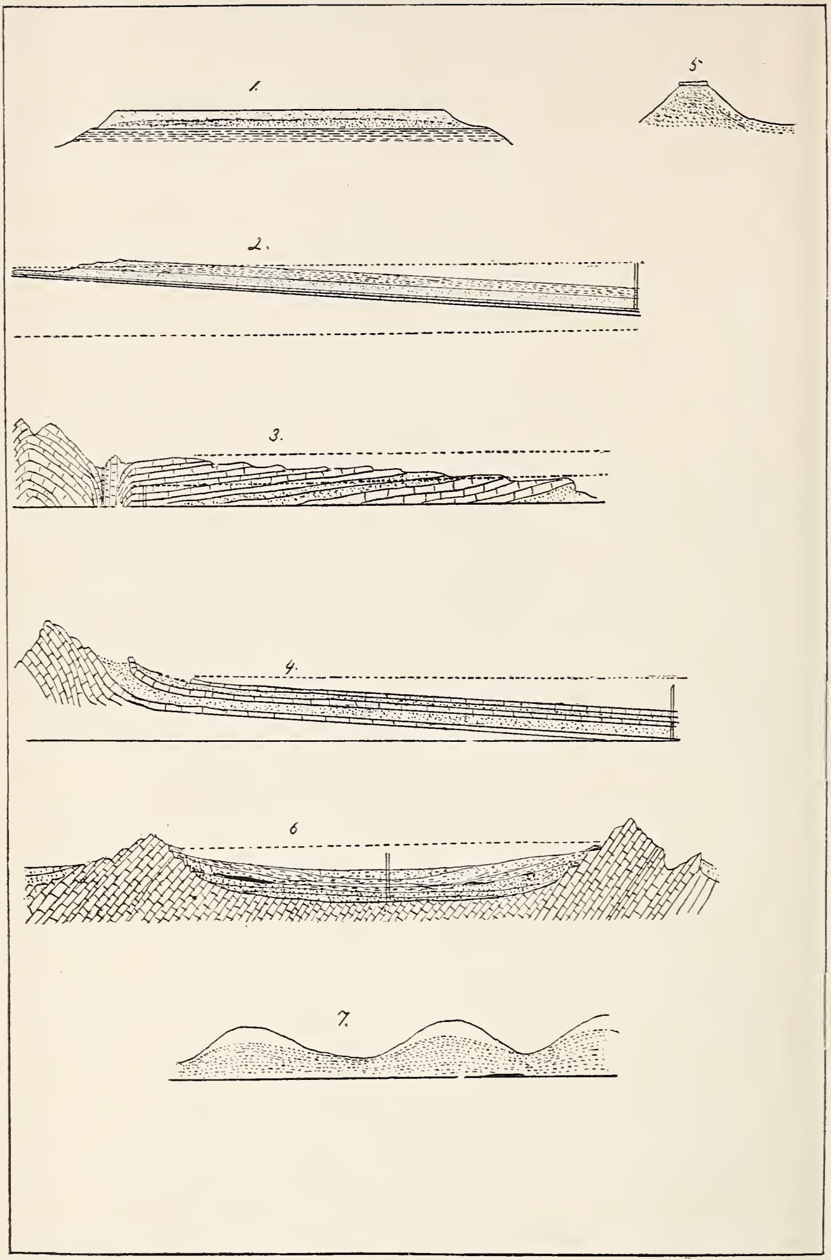
This inclination coastward with the topographic slope is contrary to that of the adjacent Paleozoic and Red Bed areas (see profiles), which incline usually to the west and against the topographic slope. It is also different from the Trans-Pecos Mountains, whose rocks dip at excessive angles.

If one begin at the coast and travel westward across this region he will find that, while constantly ascending above sea level at a slight gradient, he will be descending geologically; that is, he will cross successive belts of country, each with its peculiar soil, rock, and flora, and will see that each of these different aspects is due to the rock sheet upon which the country is founded. (See profiles appended.) The soil and other surface débris, which are the weathering of the underlying rock sheets, are sandy and covered with timber, and wells are abundant if the underlying rock is sandstone; but if it is marly (chalky) clay the soil will be black, sticky, and treeless, and the water poor and scarce.

The outcropping sheets of these various strata, owing to their diverse physical and chemical composition, have weathered into diverse characters of country, forest and prairie, broken or level exactly as the substructure permits. Among those subdivisions of the coastward incline



PROFILE AND GEOLOGICAL SECTION
FROM DUBLIN TO WACO, TEXAS
SHOWING DEPTH AND SOURCE OF ARTESIAN WATERS
BY ROBT T. HILL.



Water-bearing Strata and Imbibition.

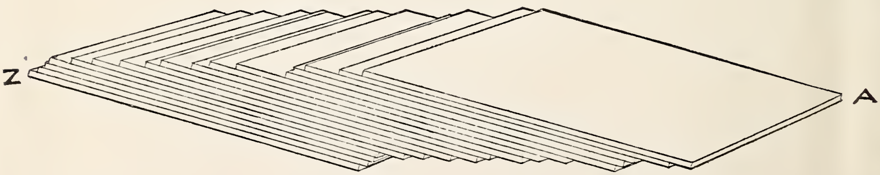


Fig. 8. Illustrating Arrangement of Strata

are the following familiar belts, each of which is as different from the others as the soil of Virginia from that of Arizona:

(1) The Coastal Prairie.
(2) The Fayette Prairie.
(3) The East Texas Timber Region; and
(4) The Black and Grand Prairie Regions and Cross Timbers discussed in the succeeding chapters.

This great series of rock sheets, a table of which is given on the accompanying plate, is composed of alternations of pervious and impervious layers presenting magnificent conditions for an artesian water supply, which will be next discussed.

These sheets, consisting of sediments deposited in and around the Gulf of Mexico during its various epochs of expansion and contraction through continental subsidence and elevation, all incline coastward at very slight angle, a little greater than the surface gradient, producing long and gentle inclinations very favorable to artesian conditions. The former western continuation of this system towards the Rocky Mountains has been degraded and destroyed by erosion and mountain folding and later formations deposited over much of it, while other portions have been entirely removed, exposing the differently inclined rock sheets of the Red Beds and the central Paleozoic areas upon which the eastward system rests unconformably. (See profile.)

By this erosion the present western edge of the main area of the coastward incline, the western border of the Grand Prairie and Upper Cross Timber regions, is constantly receding eastward.

It will greatly assist the reader to grasp the arrangement of these rock sheets if the order of succession of the main beds or formations which constitute the explored crust of the earth be kept in mind. The various strata which constitute the coastward incline are superimposed upon each other in definite order.

The arrangement of the formations of the group constituting the coastward incline may be illustrated by a package of cardboard (see Fig. 8), which may be imagined to represent the strata or rock sheets. When properly placed on the table, the topmost sheet represents the newest geological formation or coastal prairies. A few sheets immediately beneath represent the strata of the underlying Washington prairies. Each cardboard in turn represents an older rock sheet until we come to the bottom card, representing the Trinity sands resting on Paleozoic rocks. Place the pile in a northwest and southeast direction, so as to uncover the upper surface of a large number of sheets, and a very correct idea of the manner in which the various geologic formations occupy the surface of the eastern half of Texas is then obtained. *A* is the top sheet of the pile and *Z* is the bottom one; and yet both are visible. If the hand is passed from *A* to *Z* along the extended pack, it must in turn traverse the exposed surface of each sheet, until it arrives at the bottom one. Further, if instead of looking from above down upon the pack, we look at the side elevation, it will be seen that the cards are no longer horizontal; but slightly tilted from northwest to southeast; in other words, they dip to the southeast. The position of the cards may be used to illustrate the succession of various kinds of soils and waters in the region under discussion. Anyone who travels across this region in a northwesterly direction, will pass over the various strata forming the surface in a similar manner. All these strata dip towards the southeast and all crop out towards the northwest. The succession and outcrops of the various strata are shown in the section of

the country from the coast to the central denuded region. The newer formations are on the southeast, and the older formations successively occupy the country until we arrive at the Paleozoic sandstones and shales of the central region. This is the key to the succession of the various kinds of rocks in the coastward incline.

It will also be seen by beginning with the bottom sheet that the exposed face of each sheet forms an inclined plain of stratification, which is terminated to the eastward or lower edge by an ascending escarpment formed by the edge of the next higher sheet, and upon its western or highest edge by a step-off or descending escarpment formed by its own edge. This inclined plain is known geologically as a dip-plain, as distinguished from a mesa or plateau, in which all the edges are free escarpments. All the parallel belts of country of the coastward incline are dip-plains. The valley where the escarpment meets the dip-plain is known as a valley of stratification; and there are many of these in the region under discussion, the most conspicuous of which is that of the Upper Cross Timbers.

Furthermore, in traveling across these escarpments and dip-plains it will be evident that while the descents of the sudden escarpment faces are great, the gradual ascents of the dip-plains are greater in the aggregate, so that while the last valley of stratification is several hundred or thousand feet lower in the geological series, it is also several hundred feet higher in altitude, thus illustrating the paradox that the receiving areas of artesian well systems are often valleys.

Finally, if by some great strain there should be a great fracture extending across the whole pack of cards as though cut through by a knife, and one side dropped down or raised up, this would be a fault. If this fault were in the direction of the edges of the outcropping cards, it would be a strike fault; and if across the edges or the long direction of the pack, it would be a dip fault. If the dislocation or throw of these faults is great, then it will be seen that the continuity of the transmitting strata will be broken, thus seriously affecting the artesian conditions. If the down-throw be interior-ward, the receiving area may be reduced too low to afford pressure at the point where a well may be desired.

Now, it happens that throughout the vast region of the Grand and Black prairies there are two of these great fault lines—one of each kind—the first of which extends from near Dallas to Del Rio, *via* Waco, Austin, Heliotes, and Uvalde, and is a strike fault which downthrows to the eastward; while the other, which extends from near Marietta, Ind. T., southeastward through Preston, Denison, and south of Paris, Tex., is a dip fault, with its downthrow interiorward, reducing the receiving area below the altitude of most of the Red River counties of Texas, where water would be desired.

This is the simple geological structure of a country embracing the whole eastern half of Texas and southern Indian Territory, an area of over 170,000 square miles, and including all the humid and semihumid regions of the State.

It is the inclination and outcrop of the different strata that produces all the various belts of country as shown in the map accompanying this paper. Especially marked is the relation of timber to structure in this eastern division of our territory. Wherever the country is an open prairie it is underlaid by compact formations with little sand, such as clays and chalks. The coastal prairie, the Fayette prairies, the Black prairie belt, the Eagle Ford prairie, the Grand prairie, and the red beds are all of this class. Wherever the formation is sandy there are forests,

as the east Texas pine woods and the lower and upper cross timbers. Each of these different strips of country has a soil radically different from that of the others, for the soil is the surface residuum of the underlying structures.

In addition to being the fundamental cause of all natural and economic differences of the coastward incline, it will be found that these different rock sheets present a very great diversity of water conditions, in accordance with their capacity for imbibition and transmission of moisture. For instance, throughout the great Black prairie region shallow wells are difficult to obtain, owing to the poor water capacity of the clays, while in the sandy regions well water can be secured wherever dug for.

It will also be found that within this system of rock sheets of the coastal incline are several great sheets of sand, which become the receiving areas for vast artesian systems, so that throughout much of the area artesian wells can be obtained, as I shall show more specifically in the following pages. There are at least five groups of artesian water-bearing strata with corresponding artesian areas as follows:

No.	Artesian group.	Receiving area.
1	Coastal wells of Galveston, Houston, Gonzales, etc	Fayette sands.
2	East Texas or timber belt wells, Marshall, Robertson, etc	Eo-lignitic and glaucomite sands.
3	Dallas, Denison, and Pottsboro wells	Lower cross timber sands.
4	The Fort Worth Waco system:	
	Upper division	Paluxy sands.
	Lower division	The Trinity sands and alternating beds.

Each of these systems is of great importance in the economic welfare of the State, and therefore a minute description of them will be attempted in the succeeding pages.

THE EASTERN DIVISION CONTINUED.

THE COAST PRAIRIES.

The coastal portion of the main land of Texas, from the Louisiana to the Mexican border, extends inland from 50 to 100 miles; and consists of a flat usually timberless plain, elevated at its interior margin not over 200 feet above the Gulf. It dips so imperceptibly eastward that it appears to be a landward continuation of the great submarine bench of the Gulf of Mexico. From the deficient drainage, the inconspicuousness of its waterways, and its absolute uniformity of surface, it is evident that this plain is a newly-developed surface feature which has not long been reclaimed from inundation, a fact which is further attested by its want of consolidation, its substructure, and the occurrence among its fossil remains of species still existing in the adjacent waters of the Gulf. Although but a fraction of the total area of the State of Texas, this prairie is an extensive formation, occupying many hundred square miles. It is perhaps the best example of a newly-emerged coastal plain in this country. This feature can be studied along the lines of the Southern Pacific and Texas Central railways, between the Sabine and Hempstead, Tex. Stratigraphically this formation has been but little studied. The absence of timber is due to poor drainage and to the salinity and compactness of the structure. Its evolution and history are

not pertinent to this discussion, but its age is late Quaternary. Its interior margin is rolling and its transition into the next feature is abrupt. The formation, in itself, is poor in water transmission.

Beneath this plain, however, there are several sheets of artesian water-bearing strata, being the same as those constituting the surface of the next regions inland, and from which Galveston, Houston, and many other places have secured artesian water. At Houston a great number of these wells have been bored, and the city is supplied with them. They are of shallow depth there and increase towards Galveston, but at the latter place they have not been so successful as at Houston in securing pure water.

There are no doubt many of these water-bearing strata beneath the Coast Prairie, for there are several thousand feet of porous sands at slight intervals, of the Fayette sands and Eocene systems, and future experimentation will yield magnificent results as yet unattained.

While the portion of the coastal prairie in the longitude of Houston is abundantly supplied with rainfall it is an interesting fact that its southern end deflects westward into a more arid region, where no doubt the same artesian conditions exist, and will prove an inestimable benefit to the coastal country known as "southwest" Texas, where water and irrigation are greatly needed. More is said concerning this region under the head of the Rio Grande embayment.

THE WASHINGTON COUNTY BLACK PRAIRIES.

Immediately westward of the coastal prairies (which it will be remembered are composed of clay and silts) there is another region, the chief characteristic of which is its rich black sandy soil, derived from the disintegration of a friable sandstone, composed mostly of grains of quartz cemented by calcareous matrix—a great water-bearing formation, which dips beneath the coast clays and supplies the artesian waters of the Houston-Galveston system.

These prairies have been mapped out by Dr. R. H. Loughridge (see report on cotton production, tenth census) and the underlying formation described by Roemer, Shumard, and Penrose, the latter having proposed for them the name of Fayette sands.

These sands have a remarkable resemblance to the deposits constituting the Llano Estacado and contain also the peculiar opalized wood, fossil bones, and leaves resembling those of that formation, and I am inclined to believe them the same or closer allied terranes, which once extended continuously over the entire region; and I agree with Shumard* and Roemer that they are of Miocene or Pliocene age rather than Pleistocene, as has been asserted.

This formation is of great importance in that it is not only a water bearing, but throughout the area of its extent artesian wells ought to be secured from the underlying Eocene sands. The sandy strata are so pervious that they will no doubt supply the whole coastal prairie

* Dr. B. F. Shumard, in 1861, announced (see Transactions St. Louis Academy of Science, Vol. 2, pp. 141, 142) "that the discovery in Washington and adjoining counties of an extensive development of Miocene, deposits of the Mauvaisse Terre, formation of Nebraska (White River or Loup Fork?), which have yielded such a wonderful profusion of extinct mammalians and chelonians. The Texas strata consists of calcareous and siliceous sandstone, and white pinkish and grayish siliceous and calcareous marls. The calcareous beds are almost wholly composed of finely comminuted and water-worn shells, chiefly derived from the destruction of Cretaceous strata, and in places abound in fossil bones (and plants) closely allied to Titanotherium, Rhinoceros, Equus, and Crocodilus."

region with water, especially in the more arid southwest portion. Surface wells are also easily obtained in this formation.

As shown upon the map, these prairies extend across the State and occupy large areas of the southern counties immediately interior of the coast prairies.

OTHER ROCK SHEETS ALLIED TO THE COAST CLAYS AND WASHINGTON PRAIRIES.

The geology of the coastal prairies and the Washington prairies is still unraveled, but there is no doubt that each represents a coastal plain rescued in comparatively recent geologic time from the Gulf. Neither the areal extent nor the thickness of these formations has been studied and their interior margins are especially involved in obscurity. Where these margins theoretically ought to be there is evidence of shore lines, in great sheets of gravel, débris, and estuarine deposits of rivers, about which, in order to make a more complete geologic understanding of the region, a few words will be said.

The plateau gravel.—From Arkadelphia, Arkansas, due west to Eagle Town, Indian Territory, twelve miles west of the Arkansas line, and thence southwestward across the State of Texas, *via* Cameron, Austin, San Antonio, and thence around the Rio Grande embayment, there is a great sheet of shore gravel, except where worn away by more recent erosion. In Arkansas this gravel was a beach line along the southern slope of the Ouachitas. In Texas from the Red River to Austin the shore line was the level region of the lignitic Black Prairie and Grand regions. Southwest of San Antonio the shore was the great escarpment of the Edwards plateau, the margin of which is indented with the ancient estuarine valleys filled with gravel. In Northern Mexico great benches of this gravel are found against the Santa Rosa and its kindred mountains, bordering the southern line of the Rio Grande embayment, across which many areas of the gravel are still found preserved from later erosive destruction. This gravel has no important bearing upon the artesian question, because it does not dip beneath an underlying impervious formation; but it is often a valuable source of spring and well waters

The river terraces.—The second phase of interior detrital formations is the great second bottoms or terraces of the older river valleys through the Black and Grand Prairie regions. These are especially well developed in the Red, the Trinity, Little River, the Brazos, the Colorado, and the Rio Grande. They represent estuarine conditions when the Gulf shore was very near the western margin of the coast prairie. These terrace deposits, as seen at Denison, Dallas, Austin, Piedras Negras, and elsewhere are often 100 feet in thickness and form a fair reservoir for the storage of water. Springs are abundant at their contact with their underlying formations.

THE EAST TEXAS OR TIMBERED REGION.

Immediately interior of the Coast and Washington prairies, north of the Colorado, there sets in a region of country entirely different in most of its geologic and cultural aspects. This is the region of the great Atlantic Timber Belt, which marks the interior of the coastal plain from New Jersey to Texas and is well known in eastern Virginia, Maryland, the Carolinas, Georgia, Mississippi, Arkansas, Louisiana, and

Texas, to a slight distance beyond the Colorado. The soil is the same, loose sands, clays, and gravel, with its red and white tints (dependent on the oxidation of the iron), and most of the flowers, trees, and shrubs are the same; so that the traveler in portions of the District of Columbia, Virginia, or other States mentioned need not stretch his imagination to believe that in his surroundings he sees this portion of the Texas region almost as well as if he were there.

This region penetrates the northeastern portion of the State from Arkansas to Louisiana and continues southward across it towards the Rio Grande, but becomes less conspicuous and almost disappears south of the Colorado River, where the climatic conditions are more arid and later formations extend further inland. The western border of the forest belt terminates as abruptly as if stopped by some great topographic barrier, such as a lake or a desert. The abrupt termination of the forest is explained by the radical change in the structure and composition of the underlying formation; the western border coincides with the geographic extent of the pervious soils of the sandy formations and ceases where the compact supercalcareous marls of the Black prairie region begin to occupy the surface. Although mostly concealed by forest, this area of northeastern Texas has an interesting topography. In riding over it, with the view obscured by dense timber, it at first glance appears to be a succession of rounded hills; but a comparison of these with an occasional flat-top drainage divide proves that the whole country is the remnant of a great degraded but still distinguishable plain, of which the valleys are the drainage slopes. The drainage basins, because of the readiness with which the unconsolidated structure yields to erosion, occupy a far greater area than the remnants of the ancient plain in which they are carved. The present level of the rather sluggish streams is from 100 to 200 feet beneath the divides. Their flood plains or bottoms are wide and somewhat unstable. A few feet above these bottoms are the inevitable accompaniments of all the major streams of the southern cotton belt, known as second bottom, often a mile or more in width, while still above and beyond these, marking the edges of the valley, may be one or more benches, usually inconspicuous because of the unstable conditions of the unconsolidated structure and the resemblance between the transported terrace material and that of the underlying beds. The flat divides and wide valleys characterize the whole extent of the region, which, like the entire Atlantic coastal slope, is an ancient plain, whose individuality has nearly been destroyed by erosion in its reduction to the present base level, and by the elevations and subsidences which it underwent in post-Tertiary times. Within this timbered area there is a great diversity of minor topographic and geologic features, similar to those mentioned in my Arkansas report,* the most conspicuous of which are the minor prairies and gravel beds or the overlap or remnant of the interior extension of the Coast and Washington Prairie formations.

The prevalent structure of the lignitic area is alternations of unconsolidated sands and clays of a thousand or more feet in thickness, of the extensive formation known as the Eolignitic or basal Tertiary. These sands contain minute black specks of glauconite or limonite, which from the porosity of the formation quickly undergo oxidation, lixiviation, and segregation, giving the country its colors and producing stratified bands of iron ores.

Although mostly east of the limits of this investigation, it is appropri-

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* See report of geological survey of Arkansas, vol. II, 1888.

ate to speak a few words concerning the water conditions of this region. The structure, being alternations of loose sand and compact clay, presents every condition for an ample supply of water, especially when we remember the abundant rainfall. This water comes to the surface as mineral springs, many to every square mile, while wells are always obtainable if located with reasonable intelligence. Artesian wells have already been secured in many places from this formation and can be secured throughout its extent. Success is merely a question of topographic locality, for the pressure is not sufficient to cause a flow upon the high divides except along the western margin of the area, but good flowing wells can no doubt be obtained in all the lowlands.

THE CRETACEOUS PRAIRIES, INCLUDING THE CROSS TIMBER REGIONS.

The chalky prairies of Texas and Indian Territory are one of the most unique and extensive geographic features of the United States, and entirely different in every scenic and cultural aspect from most of the western plains. They begin immediately west of the great Atlantic timber belt (or Eolignitic region) in Indian Territory and Texas, and extend westward to the Coal Measures and Red Beds west of the upper Cross Timbers, north of the Colorado River, the Trans-Pecos Mountains, and the basins west of that stream. Northward these prairies are limited by the Ouachita Mountains of Indian Territory. Their southern border is buried beneath the Quaternary débris of the Rio Grande embayment as far as Eagle Pass and the mountains of Mexico.

This region, with its different prairies, each covered by its peculiar vegetation, its sweeping plains, and diverse valleys, its undulating slopes clad with mottes of live oak, its narrow strips of cross timbers, its ragged buttes and mesas, presents a landscape varied, yet possessing as a whole an individuality peculiarly its own. All these features, with their different tints of soil and vegetation and their varied conditions for human habitation, are but the surface aspects of the system of chalky rocks (chalky sands, clays, and limestones) upon which is founded and to which is primarily due every physical quality of the country. It is the great chalky region of the United States.

This prairie region is also by far the most important and fertile portion of the State, and is the seat of its densest population, owing to the great productivity of its calcareous soils, upon which are situated the most important inland cities, such as Paris, Bonham, Denison, Sherman, Gainesville, Fort Worth, Dallas, Waco, Weatherford, Taylor, Belton, Temple, Austin, New Braunfels, San Marcos, San Antonio, Uvalde, and Del Rio.

To these strata the State owes a large part of her agricultural and general prosperity, for they are the foundation of the rich black-waxy and other calcareous soils of those regions. In addition to their agricultural features, they are the most productive source of building material; while adjacent to their line of parting, extending the entire length of the State and dependent upon their stratigraphy, is a remarkable area of natural and artesian wells, as seen at Fort Worth, Austin, Waco, Taylor, San Marcos, and elsewhere.

This country is uniquely Texan as far as the United States are concerned, constituting a distinct geographic region which, in every topo-

graphic, economic, and cultural aspect, should not be confused with other portions of our country. It covers an area of over 73,512 miles, or over one-fourth (28.27 per cent) of the total area of Texas; forming a broad belt of fertile territory across the heart of the State, from the Ouachita Mountains of the Indian Territory and Arkansas to the Mountains of northern Mexico—an area larger than the average American State, and equal to the combined area of all the New England States. One-third of this region lies north of the Colorado River, and the remainder to the southwest.

These formations belong to two great rock systems, or series, an upper or Gulf series and a lower or Comanche series of Cretaceous age.

THE MAIN BLACK PRAIRIE REGION.

Immediately interior to the sandy lignitic area, and radically differerent from it, lies the main Black Prairie, the richest and largest continuous body of agricultural land in Texas, and hence the most important in cultural as well as scientific aspect.

This occupies an elongated area extending the length of the State from the Red River to the Rio Grande. The eastern border of the Black Prairie is approximately the southwestern termination of the great Atlantic timber belt. The Missouri Pacific and the International railroads from Denison to San Antonio, and the Southern Pacific from San Antonio to Del Rio, approximately, mark the western edge. A little south of the center, along the Colorado River from Austin eastward to the Travis County line, near Webberville, the Black Prairie is restricted to its narrowest limits. From this point it widens in both directions until its broadest margins, over 100 miles in width, rest near the Red and (Rio) Grande rivers. The topography of the area was well defined some forty years ago by Dr. Ferdinand Roemer as the "*sanftvelliges Hüegelland*," or "gently undulating regions." Viewed from a distance it is apparently level, but closer inspection shows it to consist of many gentle undulations which differentiate it from the topography of other prairies.

Westward the Black Prairie is succeeded by a region with some superficial resemblance to it, and usually confused with it, which, however, on closer study is found to differ from it in all essential points. This is the Grand or Fort Worth prairie, or "hard limerock region," described elsewhere. The so-called mountains west of Austin are the remains of the Grand Prairie. In general, the Black Prairie region consists of a level plain, imperceptibly sloping to the southeast, varied only by gentle undulations and deep wide drainage valleys, void of precipitate canyons. It is cut through at intervals by larger streams, the valleys of which make indentations into the plain, but not sufficient to destroy the characteristic flatness of its wide divides, remnants of the orginal plain or topographic level which have not been completely scored by the later and more youthful drainage system. The altitude of the plain is between 400 and 600 feet. The surface of most of the Black Prairie region is a deep black clay soil, which when wet becomes excessively tenacious, from which fact it is locally called "black waxy." The soil is rich in lime, which, acting upon the vegetation by complicated chemical changes, causes the black color. The region is exceedingly productive, and nearly every foot of its area is susceptible of a high state of cultivation. Large quantities of cotton, corn, and minor crops are annually raised upon these fertile lands, and if there were facilities for water and proper transportation it would soon be one of the leading farming districts of our country.

With the exception of streams which rise in other regions to the westward, and cut through it, the Black Prairie region has few running water-courses; so that along with its excellent soil it has the drawback that for domestic purposes its inhabitants have mostly depended upon cisterns or ponds, both of which have proved most unhealthful. The reason of this absence of surface waters, as will be shown later, is the great imbibing capacity of its soils and rocks.

This region in Texas is very conspicuously divided into two sections, the larger and more important of which is north of the Colorado, while the other occupies the great embayment of the Rio Grande in Texas and northern Mexico.

The main Black Prairie proper does not appear in Indian Territory. A small area of the Eagle Ford Prairie in the Chickasaw Nation, known as Carriage Point Prairie, north of Denison, has been erroneously classed with it. There are also small spots of it in southwest Arkansas, as described in my previous report on that region. (See Neozoic Geology of southwestern Arkansas; vol. 2, Report of State Geologist. Little Rock, 1888.)

THE NORTHERN DIVISION OF THE BLACK PRAIRIE.

The division of the Black Prairie north of San Antonio is subdivided longitudinally into four parallel strips of country, differing slightly, and distinguishable only by slight differences in topography and in the underlying rocks. The easternmost of these divisions north of the Brazos River is distinguished by the occurrence of sand in its black soil, and occasionally pure belts of sand. Between the Brazos and Colorado rivers, however, the sand is hardly perceptible, while in the southern division, or Rio Grande embayment, it attains great development. Immediately interior of this strip is located the largest and most characteristic belt, which is marked by the stiffest of the black-waxy calcareous clay soils. Upon digging throughout this area, the substructure is found to consist of a light-blue marl, called by the residents, "soapstone" and "joint clay," from its jointed and laminated structure. The surface, especially of the high undrained divides, is also accompanied in many places by minute depressions known as "hog wallows," which are produced by the drying, cracking, and disintegrating character of these excessively calcareous clays in poorly-drained places. This, the main portion of the Black Prairie, constitutes fully two-thirds of its total area. The cities of Greenville, Terrell, Corsicana, and Kaufman are situated near the eastern border of the sandy and black-waxy strips. Manor, Clarksville, Cooper, Taylor, and Temple are all situated in the main black-waxy belt.

An outcrop of "white rock" or chalky country, forming a narrow strip averaging 2 miles in width, extending from Sherman to the Rio Grande east of Del Rio, succeeds on the west the main black-waxy belt. This chalk belt is marked by a topography more rounded and more deeply incised, but still devoid of the sharper lines of stratification which characterize the Grand Prairie region. It is occasionally marked by clumps of handsome evergreens and oaks.

The western edge of the chalky belt, as seen at Oak Cliffs, near Dallas, and at Sherman, Hillsboro, and other places, is an escarpment overlooking a valley containing the minor Black Prairie and lower Cross Timber strips. This escarpment is continuous except where cut by rivers, from Austin to Denison, 200 miles above the depression occupied by the Cross Timbers to the west. Like every other slight inequality of

the earth's surface in Texas, this scarp is locally called "mountains." I propose for this scarp the name of Oak Cliffs or White Rock scarp. This escarpment can be distinguished upon even ordinary maps by the small fringework of minor streams which rise at its summit and drain the dip plain to the eastward, and by the streams deflected by its strike and flowing at its base. The chalk or white rock forming the summit of this scarp is the immediate geologic antecedent of the marly clays underlying the main black-waxy area, and the one succeeds the other by easy transitions; hence I classify the white rock as a subdivision of the Black Prairie region. The chalk marks the western border of the main body of the Black Prairie region throughout its extent, but seldom has an areal outcrop of more than 1 or 2 miles in width.

THE EAGLE FORD PRAIRIE REGION.

Immediately west of the Oak Cliff scarp and in its valley there is, especially north of the Colorado, another long, narrow, black waxy strip of country. This is especially conspicuous in Hill, Dallas, Grayson, Collin, McLennan, and Bell counties. (The Sixth ward of Austin is typical of this subdivision of the Black Prairie.) It is intermittent in Travis County, and occurs along an exceedingly narrow north and south line in eastern Williamson, central Bell, and central McLennan counties, the south Bosque marking its extent in the latter county south of the Brazos. North of the last-named stream it begins slightly to widen in area, and continues as a narrow belt, averaging 10 miles in width, northward through eastern Hill, eastern Johnson, western Dallas, western Collin, and western Grayson counties, for 180 miles, to the Red River. This prairie increases in area northward from the Colorado River to Red River, lying west of the White Rock scarp, and east of the Lower Cross Timbers. In Grayson County the belt abruptly turns eastward at a right angle, and runs down the upper slopes of the Red River Valley, through Grayson, Fannin, and Lamar counties, to the eastern edge of Red River; Sherman is situated at its inner angle, and its southern margin is approximately marked by the transcontinental branch of the Texas Pacific Railway, from Sherman to a few miles east of Paris, in Lamar County. The southern border of this eastern Red River area is not marked by an escarpment, but by an inconspicuous fault line. Some of the richest agricultural lands in Texas are located upon this inner Black Prairie region, and its soil is usually fertile in most places.

The portion of the Black Prairie southwest of the Colorado presents many radical differences from the portion north of that river. It deflects westward into a more arid country, and instead of ending with a descending escarpment to the westward it is abruptly terminated by an ascending one—the great eastern escarpment of the Edwards Plateau. Besides these differences the whole region is covered with a thin sheet of sandy and gravelly débris, the remnant of the sea beach which in very late times extended from the southwest corner of Arkansas across the State of Texas via San Antonio to Del Rio. Owing to the presence of this Quaternary débris, and the great development of sand in the beds of the Cretaceous, together with marked differences in the other physical aspects, I have separated this southern region from the Black prairies, and discuss it separately under the caption of the Rio Grande Embayment.

THE LOWER CROSS TIMBERS.

The western and northern border of the northern division of the Black Prairie region is terminated most abruptly by a narrow strip of timbered sandy land, extending from the Brazos to Red River, and thence down the valley of the latter stream nearly due east to Red River country, known as the Lower Cross Timbers.

Although seldom exceeding 10 miles in width, this remarkable belt of timber is nearly 180 miles in length from south to north, and over 100 miles east and west from its great bend in northwest Grayson County.

The occurrence of this peculiar ribbon of upland timber between two vast stretches of prairie had long been a subject of inquiry until the writer, in 1887, investigated and published * its geology, and showed that the cause of this forest growth was the sandy soil and substructure, which was the outcrop of a rock sheet marking the beginning of the Black Prairie series of rocks.

The Lower Cross Timbers are composed of white sands and sandy clays, oxidized at the surface into ferruginous masses. Viewed from the Oak Cliff or White Rock scarp, looking westward, these timbers appear to occupy a valley, but when observed from the westward, as from Fort Worth or any point on the eastern margin of the Grand Prairie region, they apparently occupy a higher level to the eastward, appearing as low, rounded, wooded, mamillary hills.

The Lower Cross Timbers and the sands in which they grow, for some unknown reason, disappear south of the Brazos. From that stream they extend due northward to the bluff of the Red River, in Grayson County; thence they extend due east down Red River, first touching that stream in eastern Grayson County. From this point the river flows in the line of the timber to Pine Bluff, Lamar County, apparently finding in the soft sands and clays an easy passage way for its winding channel.

By the peculiar fault north of Denison the northern member or narrow east and west belt of the Cross Timbers in that country is split in its length, the northern half appearing 30 miles distant in Indian Territory, extending south of old Fort Washita from the Washita River to the Boggy.

The Lower Cross Timbers are admirably adapted to fruit-growing, and, as will be shown later, play a most important part in the question of artesian water.

To appreciate the water conditions of this vast region it is necessary for the reader to know the sequence of the great rock sheets of the Black Prairie and Lower Cross Timbers that compose it, their water bearing and transmitting capacity, as well as their elementary topography.

GEOLOGICAL SUB-STRUCTURE OF THE BLACK PRAIRIE REGION.

The rock sheets of the Black Prairie region are epitomized in the vertical section before given. The sandy soil of the eastern margin is the outcrop of the upper Arenaceous or Glauconitic division, No. 5 of our section; the main Black Prairie division, the surface of the chalky clays, called Penderosa marls, No. 4; the White Rock escarpment, the

* (See Geology and Geography of the Cross Timbers of Texas, American Journal of Science, April, 1887.)

PROFILE and GEOLOGICAL SECTION from

MILLSAP to TERREL TEXAS

Showing Depth and Availability of Artesian Water Bearing Strata

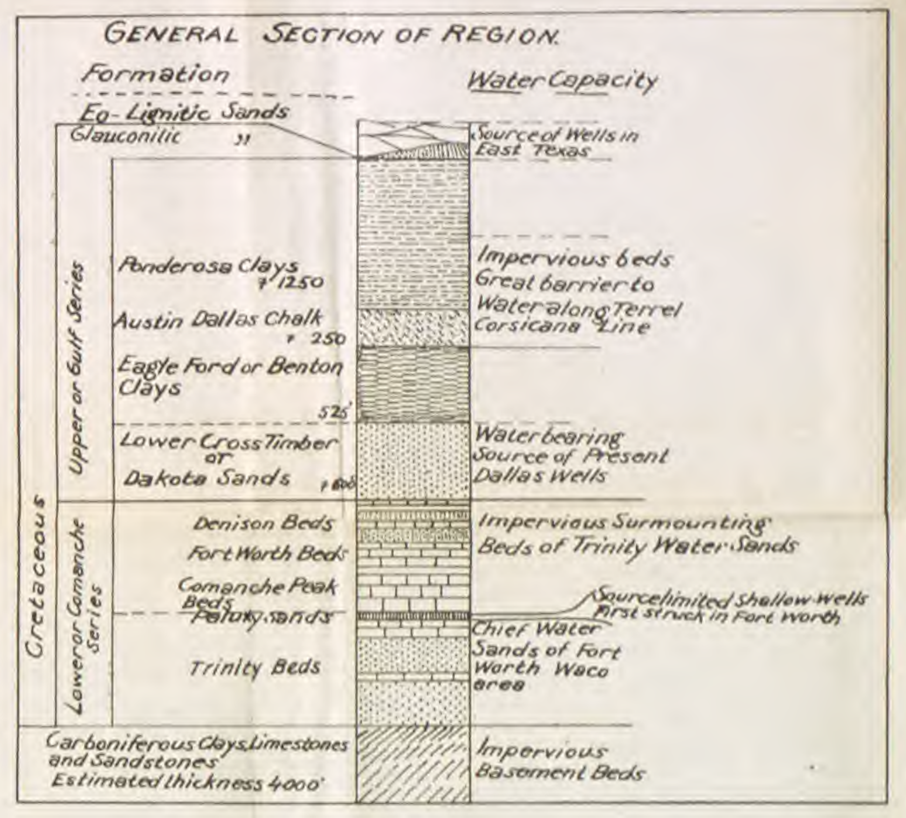
by Robt. T. Hill

Horizontal Scale ½ Inch to 1 Mile

Vertical Scale 1 Inch to 1000 Ft.

| Flowing Wells

To determine the depth of any water bearing Stratum at any point multiply the distance in miles of that point, from the lowest out crop of the receiving beds by the dip in feet, per mile (33) and subtract therefrom the difference in altitude between the two points.



outcrop of the Austin-Dallas chalk, aggregating about 300 feet in thickness, No. 3; the Minor Black Prairie, No. 2 of our section, is also composed of a sheet of clay, somewhat like those of the main division, and hence the similarity of its topography with that of the Lower Cross Timbers, No. 1. These are the rock sheets for which I have chosen the name of Black Prairie series. These sheets with their water capacities will now be described in ascending order, beginning with the lowest beds of the series.

THE LOWER CROSS TIMBER BEDS, OR DAKOTA SANDS.

From the Brazos River northward and eastward along the Red River the base of the upper series is composed of a brown, more or less ferruginous, predominantly sandy deposit, resting unconformably upon various horizons of the beds of the Washita division, or top of the Comanche series. These sandy deposits present an infinite variety of conditions of cross-bedding, clay intercalations, lignitic patches, and vary in minuteness of size and angularity of the uncemented particles, characteristic of typical littoral deposits, while occasionally there are found fossiliferous horizons.

The beds are well displayed along the line of the Missouri, Kansas, and Texas roads, between Denison and Whitesboro, Denton and Lewisville, and Alvorado and Fort Worth. There are also many bluffs along the Red River where the sand appears to advantage, as Pine Bluff, Sowells Bluff, and others.

These sands differ from those of the Upper Cross Timbers, to be discussed later, in that they contain much more iron and mineral salts.

In the southern and western suburbs of Denison these sands are greatly developed. South of the Brazos River, and at Austin, they are entirely missing, a fact that may be explained in connection with certain changes of level which took place just after they were laid down, exposing them to erosion before the next division was deposited.

The Lower Cross timber strata decompose at the surface into rich sandy soils, which have not been studied minutely. These support a vigorous timber growth, its structure being especially favorable for deep-rooted plants. In age and character these sands are the same as the celebrated Dakota sands of Kansas and Dakota, and equally valuable in relation to the water supply, since they possess great capacity for imbibition. They are the receiving area for the artesian wells at Pottsboro, Dallas, and Midlothian, and when properly understood many other wells will probably be found, as will be discussed later. They increase in thickness toward the north and become more frequently intercalated with clay.

The artesian wells at Dallas have penetrated as yet only about 50 feet of them, but at Denison they are at least 200 feet thick, while at Paris they are still thicker.

The area, extent, and variations of this rock sheet are important factors, since it is the present water-bearing stratum of the Black Prairie region.

The Eagle Ford or Benton clay shales.—These lie to the eastward and immediately above the Lower Cross Timber Sands, from which it is difficult to separate them, and are the foundation of the minor Black Prairie strip.

Beneath the scarp of the White Rock (Austin-Dallas) chalk at Dallas and extending westward through the Mountain Creek country to the Lower Cross Timbers can be seen typical localities of this division, the

thickness of which I estimate at 500 feet. In their medial portion they are dark blue and shaly, highly laminated, and occasionally accompanied by gigantic nodular septariæ, locally called turtles, which have often proved a serious obstacle to well drills. The uppermost beds become more calcareous, grading rather sharply into the chalk. There are also occasional bands of thin, impure limestone, which are readily distinguishable from all other cretaceous limestone by their firmness and lamination. Fossil remains of marine animals are also found in these clays, including many well-preserved species, the delicate color and nacre of the shells being as fresh as when the animals inhabited them.

At Austin these beds occur with less thickness, and at one place where Tenth street crosses Shoal Creek they are entirely missing, the chalk resting upon the Shoal Creek limestone. The northwestern part of the city is underlaid by these clays, which are here more calcareous and accompanied by beds of laminated limestone. South of the river, along the International Railroad, they are finely displayed in Bouldin Creek, with the characteristic blue color on fresh exposure. They also appear at San Antonio, near the cement works, and at New Braunfels, Uvalde, and other points. At Waco they form the bluffs of the Bosque, at Prather's farm, and the fish pond. North of Waco they increase in extent and thickness, forming extensive black-waxy areas in Hill, Johnson, Ellis, Dallas, Lamar, Fannin, and Grayson counties, west of the White Rock scarp. This formation is a retaining or impervious rock sheet, overlying the sands, and is not a receiving area for water.

The chief economic value of the minor Black Prairie will always be its magnificent black, calcareous, clayey soil; while some of the chief geological considerations are the ascertainment of means to make this soil more easily handled and less tenacious by devising suitable mixtures, the discovery of road-making material, and the increase of water for agricultural and domestic purposes. Owing to its clay foundation the soil now retains for plant use treble the quantity of moisture of some of its adjacent sandy districts, but surface and flowing water is almost absent.

Fortunately, however, this district is also within the Central Texas artesian area, and an abundant supply of water can always be obtained south of Sherman at a depth of less than 1,500 feet; as has been proved in the course of our investigations. When this fact is fully appreciated the region will be one of the most prosperous in Texas. In the valleys of most of the streams running eastward across the east half of the minor Black Prairie, another flow of artesian water, the same as at Dallas, can be obtained at from 100 to 300 feet. The source of this water is in the Lower Cross Timber sand.

The medial and lower portions of these shales are at places bituminous, as at Austin, Fiskville, Waco, San Antonio, and frequently an appreciable amount of rock oil, appears upon the surface of the waters obtained from them; but so far there have been no indications to justify expectation that this soil occurs in any commercial quantities, the fact being rather against such a conclusion. The clays increase greatly in thickness to the northward, growing gradually less distinguishable from the Cross timber sands in the Red River country, where they can be seen in many places from Bell to Paris. At Dallas they are 525 feet thick.

The Austin-Dallas chalk.—This is the thick stratum of white rock or chalk occurring in the scarp along the western border of the main Black Prairie and separating it from the minor Black Prairie region.

The outcrop of this chalk begins in the southwest corner of Arkansas, but is not found in the Indian Territory. It crosses the Red River, but owing to the faulting does not appear westward up the south side of the valley of that stream until reaching Sherman, from which place it deflects southward, passing near McKinney, Dallas, Waxahachie, Hillsboro, Waco, Belton, Austin, New Braunfels, San Antonio, and Spofford Junction, beyond which it bends northward, appearing in the true mountains in the vicinity of El Paso and New Mexico. It is distinguished above all by its peculiar chalky substructure, and so resembles some of the beds of the underlying Comanche and of the overlying Upper Cretaceous that until recently they have not been distinguished from them. Upon close examination, however, it is noticeable that the Lower Cretaceous beds of the Grand Prairie are more distinctly stratified and very much harder and generally more crystalline through pressure, solution, and redeposition of the carbonate of lime in the chalk. The topography of the Austin chalk beds is also of a milder type than that of the Comanche series. Above all, it is distinguished by its softness and by its entirely different fossil remains. It is also distinguished from the other chalky beds of the upper Cretaceous by its great firmness and by a higher percentage of calcium carbonate.

The rock of this formation is massive, nearly pure, white chalk, usually free from grit, and easily carved with a pocketknife. Under the microscope it exhibits a few calcite crystals, particles of amorphous calcite, and innumerable shells of foraminiferæ. The air-dried indurated surfaces are white, but the saturated subterranean mass has a bluish-white color. The rock weathers in large conchoidal flakes with an earthy fracture. In composition it varies from 85 to 94 per cent of calcium carbonate, the residue consisting of magnesia, silica, and a small percentage of ferric oxide, as can be seen from the following analysis of random specimens, while the upper Cretaceous beds have only from 20 to 50 per cent:

	Texas.	Rocky comfort.
Calcium carbonate	82.512	84.48
Silica and insoluble silicates	11.451	9.77
Ferric oxide and alumina	3.648	1.25
Magnesia	1.189	Trace.

The thickness of this chalk is about 300 feet. As far as observed in Texas it averages the same thickness at Austin and Dallas. It is of great uniformity throughout its extent, but there are a few local differences in hardness, which are sometimes due to surface induration and to igneous action, having been converted into marble at Pilot Knob, south of Austin.

In the vicinity of Austin the soft chalky structure is somewhat destroyed by erosion and volcanic disturbances of the vicinity as the deposition of volcanic débris, and excessive jointing and faulting show, but it maintains its pure chalky aspect elsewhere.

A great portion of the former extent of it has been destroyed by erosion, and its western border in central Texas is now receding eastward under the influence of excessive atmospheric decomposition and denudation.

This chalk is the white rock which underlies Fairview Park and most of the city of Austin. Waco is also built upon it; the Lovers Leap west of that city being one of the finest chalk bluffs in America.

Oak Cliffs, the suburb of Dallas, as well as that city are built upon it, and also Sherman. It imbibes considerable moisture, but transmits none to speak of. Its chief value south of Dallas is that it is a landmark by which artesian wells can be located and their depth predicted with much certainty, as will be shown later.

The Taylor (or Exogyra ponderosa) Marls.—The eastward continuation of the Austin-Dallas chalk is covered by one of the most extensive and valuable, but least appreciated, geological formations in the United States, a remarkable deposit of chalky clays, aggregating some twelve hundred feet in thickness, according to reported well borings and estimates of the normal strip. In fact these clays are so little known that no popular name has been found for them, and hence they are called from an immense fossil oyster which is found in them. They occupy the whole of the Main Black Prairie region east of the Austin-Dallas chalk, and form the basis of the rich, black, waxy soil. Notwithstanding their areal extent, good outcrops of unaltered structure are seldom seen, owing to their disintegration. Usually they are seen only in ravines, creeks, or fresh diggings. However, at the Blue Bluffs of the Colorado, 6 miles east of Austin, a good exposure is afforded, where these clays can be readily studied and diagnosed. They are of fine consistency, unconsolidated, and apparently unlaminated until exposed to weathering, when their laminated character is developed. They are light blue before atmospheric exposure, but rapidly change into a dull yellow, owing to oxidation of the contained pyrites of iron. Their accessory constituent is lime in a chalky condition, and they make a black calcareous clay soil, characteristic of chalk and chalky clays, whenever their excess of lime comes in contact with vegetation.

Their middle portion is apparently void of all well-preserved fossils, yet impressions are abundant in places. Toward the top, as seen one mile north of Webberville, ten miles east of Austin, they become slightly arenaceous and concretionary and very fossilferous, indicating graduation into the glauconitic division. The fauna of these concretionary clays at Webberville, Corsicana, and elsewhere begins to partake of the character of that of the glauconitic or New Jersey division, and yields an abundance of fossil species.

Although not the top of the Cretaceous system, the Webberville beds are the highest exposures seen along the Colorado River section, for at that place they are overlaid by the lignitic or basal division of the Eocene Tertiary. To the north of Webberville, these sands become more extensive.

The economic value of these chalky clay marls lies in the fact that they are the foundation and source of the rich soil of the main Black, Waxy Prairie of Texas, the largest continuous area of residual agricultural soil in the United States, apparently inexhaustible in fertility; for as the farmer plows deeper and deeper he constantly turns to light the fertile marls which renew the vitality.

As before remarked, the water conditions of the formation are very poor and the absence of a healthful domestic water supply has been one of the greatest drawbacks to the region. The very characteristics of the formation that constitute its chief value for agriculture decrease its water conditions. The thick clays can imbibe moisture but slowly, and when saturated retain it, instead of transmitting it, as would a more sandy sheet. The surface wells are difficult to secure and the streams are sluggish and dirty.

Artesian water is the great need of the main Black Prairie region, and to reach even the first water-bearing sand (that of the lower Cross

Timbers) will require the penetration of two great impervious sheets, the Austin chalk and the Eagle Ford clays, in addition to the depth of the ponderosa marls, beneath the desired locality. Upon the extreme eastern edge of the outcrop (its thickest portion) two wells, one Terrell and the other Thorndale, have penetrated 2,100 and 1,700 feet, respectively, without reaching the bottom of the Black Prairie series.

The Uppermost or Glauconitic Division.—This division is the uppermost continuation of the Ponderosa marls, its chief difference being that the clays, chalks, and sands become glauconitic as we ascend, and that there are conspicuous changes in the fossils, which become more plentiful, the species of fauna partaking of the same characteristics that distinguish the Cretaceous of the New Jersey and Alabama regions, which are of the same formation. This division as it occurs in southwest Arkansas has been minutely described in my Arkansas report, but its whole detail remains to be developed in Texas, its occurrence having been affirmed only in one or two places without specific, detailed study.

The glauconitic or greensand beds are mostly concealed beneath the overlap of the Tertiary and Quaternary beds, throughout their whole extent, from New Jersey to the Rio Grande, and in general it is only where these have been eroded away that they obtain an outcrop.

They are first seen in two small spots in Bowie County, north of De Kalb Station, upon the Friese place, where they occur beneath the overlapping Tertiaries. This mode of occurrence is geologically known as an "inlier," and there are several more of these glauconitic inliers to the eastward as far as Smith and Anderson counties, all of which are in the direct line or strike of the Arkansas beds, which they resemble in every detail.

To the westward, however, these beds become more conspicuous, and they attain considerable development in the southern half of the Red River tier of counties as far west as Bonham, whence they deflect southward, constituting the eastern margin of the Black Prairie as far south as Webberville, on the Colorado.

Commencing in the eastern Red River country, they extend westward to the sandy beds of the division, outcropping as far west as Ladonia, Fannin County, and covering much of Delta, Hunt, Rockwall, and Navaro counties, the brownstone marls outcropping interior of the sands in Kickapoo, Red River country, and south of Paxton, Lamar County.

The chalky beds of the glauconitic division (not to be confused with the Dallas chalk) and the similar chalks (the White Cliffs chalk and sub-chalk of my Arkansas section) outcrop from Clarksville, via Paxton and Honey Grove, nearly to Bonham, but do not persist southward.

In the Rio Grande embayment, southwest of San Antonio, east of Del Rio and the Santa Rosa Mountains of Mexico, these beds again attain an enormous development, but entirely different in detail from the north Texas extension, indicating vast difference of condition in the region during the closing epoch of the Cretaceous, and resemble very much the Fox Hills and Laramie beds of the Northwest.

These beds are well displayed from Eagle Pass to the Webb County line in Texas, and south of the Sabinos, between Santa Rosa and Tampico, Mexico. They consist mostly of the glauconitic sands alternating with limestones, clays, and beds of lignitic coal. At Eagle Pass they are fully 700 feet thick, and the whole formation may be even greater. The beds abound in fossil wood and bones, and are of great economic value as coal-producers, the mines at San Felipe, Eagle Pass, and Santa Rosa being of this formation.

THE GRAND PRAIRIE OF TEXAS AND INDIAN TERRITORY.

This geographic feature is characterized throughout by the peculiar limestones and clays of the Lower Cretaceous formation, upon which it is founded. It differs from the Black Prairie region proper in nearly every physical feature. In general it is more elevated, its plateaus are flat instead of undulating, and its valleys are more precipitate, being benched and terraced through the unequal resistance and varying hardness and its alternate stratification. Its soil, except in valleys, is generally shallow and rocky, while its color tends to yellow and chocolate brown, instead of black. The chief difference however is in the hardness of the underlying rocks, which are the foundation of all the above features. These compose a beautiful substructure, whose hundreds of feet of white chalk and yellow magnesian layers of alternating degrees of hardness give to the landscape individual tone and topography not found elsewhere in America. The western border of this region is carved into a rugged scarp accompanied by outliers of terraced buttes and mesas. Its interior margin begins at the Arkansas and Indian Territory line at the crossing of Little River, and extends westward 165 miles in the Territory along the southern slope of the Ouachita Mountains to the west of Marietta, from which point it turns gradually due southward across Texas.

The stratification of the central area of the Grand Prairie is almost horizontal, dipping eastward less than 1 per cent, a slightly greater angle than the topographic slope. In the region of the Edwards Plateau the dip is less, and approximately corresponds in inclination with the surface of the plateau. In color, composition, and scenic effects these rocks and their stratification resemble no other region of North America, but they are said by those who have seen both regions to be identical in appearance with the Cretaceous and Jurassic rocks of eastern France and Switzerland. To this structure and its methods of disintegration is due the individuality of the topography of the Grand Prairies.

After each season or rainfall the ordinary hue of dry grass is succeeded by varied flowers of indescribable beauty. The soil is usually shallow and is the residuum of the chalky substructure, which is of varying degrees of induration. Its prevalent color is dark chocolate, which readily distinguishes it from all other limestone soils in the State. Although differing in altitude, topography, and structure from the Black Prairie region, this section is not distinguished from it by some people. Owing to the shallowness of the soil and the different conditions of rainfall, but few upland areas of the Grand Prairie are adapted to agriculture, while nearly every acre of the Black Prairie can be utilized. The underlying structure of the Grand Prairie is that of the Comanche series, consisting of alternations of chalky limestones and marls of varying degrees of induration and thickness. These rocks are so much harder than the Upper Cretaceous sediments underlying the Black Prairie region that the region has been appropriately called the hard lime-rock region.

In Texas the eastern margin of this plain, separating it from the Black Prairie region, extends almost southward from Denison via Whitesboro, Denton, Forth Worth (6 miles east), Cleburne, McGregor, Belton, Georgetown, Round Rock, and Austin, to the Colorado, whence it sweeps south and westward, approximately west and north of the line of the International and Great Northern and Southern Pacific railways. From Denison this line is marked by an ascending escarpment (that of

the Austin chalk) as far south as Waco, and thence on by the western border of the Lower Cross Timbers. South of this line the margin of the Grand Prairie is marked by a descending escarpment, the Balcones fault, overlooking the Black Prairie and the ancient embayment of the Rio Grande.

The interior border is more jagged and irregular in outline, but everywhere, with the exceptions of the western border of the Stockton division, is marked by a descending escarpment overlooking the escarpment valley of the Trinity Sands (upper cross timbers) or other lower formations upon which it rests. This line is rapidly receding eastward, from the destructive erosion, thereby producing the serrated and irregular appearance. The edge of the surmounting plateau is from 300 to 500 feet above its base, and everywhere overlooks the lower and different Paleozoic region, upon which it borders. Owing to innumerable alterations of hard and soft layers, it presents a series of alternate benches and terraces of stratification, which are of uniform contour and extent through long distances, and greatly resemble water made terraces of lake shores.

The line of this escarpment is very irregular, forming innumerable curves and points. Sometimes it follows the crossing rivers until almost the eastern margin of the region is reached, as at the valley of the Colorado near Austin. The entire length of this scarp, with its principal meanderings across Texas, can be little less than 2,000 miles. Accompanying this scarp are innumerable circular flat-topped buttes, outliers of the main plateau, which have been completely separated from it by atmospheric erosion and now fringe the entire margin. These are typical "buttes," the level mesas or tops of which are capped with the identical stratum and geological horizon which surmounts the main plateau of the Grand Prairie. In symmetry of proportion and horizontal position of the composing strata, and in clearness of every detail of structure, there are no grander or more unique examples of atmospheric erosion in our country. Often these buttes, like Double Mountain, in Stonewall County, are 40 to 100 miles from the main area of the Grand Prairie, and invaluable landmarks in tracing the history of its degradation. Among the most characteristic and typical buttes are Comanche Peak, Hood County; Double Mountains, Johnsons Peak, Round Mountain, Santa Anna Mountain, San Saba Peak, Church Mountain, Castle Mountain, Pilot Knob, Williamson County; Two Star Mountain, in Hamilton and Comanche counties, and Post Mountain, in Burnet County.

It seems clear that these escarpments and mesas are the effect of erosion, and they illustrate the rapid disintegration the region is undergoing. If this be true, it requires no stretch of the imagination, especially when the fragmental patches like Santa Anna and Double Mountain are considered, to see that but a short time since in geological times the rocks of the Grand Prairie extended westward to the region now overlaid by the Staked Plains, completely covering the central Paleozoic areas and the Red Beds region of the State. Much of the erosion took place in the Llano Estacado epoch and converted the débris into that formation.

All along the thirty-second parallel from Sweetwater to Pecos it can be seen that the western border of the Grand Prairie formation is buried beneath the Llano Estacado formation, without any well marked or defined escarpment. West of the Pecos and southeast into Mexico as far as Santa Rosa the western border of the Grand Prairie is broken by great mountain uplifts, which have folded, faulted, and tilted at every angle.

Thus the northwestern margin of the Grand Prairie region in Indian Territory and Texas is being destroyed by erosion. A narrow central neck between the Pecos and the Colorado is buried beneath the Llano Estacado formations, and its southwestern edge is broken by the great mountain uplifts of that region.

The Grand Prairie has many diverse surface features, dependent upon the character of the underlying beds. The eastern margin is usually composed of treeless dip-plain prairies with a black or brownish soil derived from the underlying beds of the Washita division. The Caprina limestone and Comanche Peak beds usually outcrop as the cap and escarpment of the buttes and mesas. At the base of these there is usually a wide valley of fertile chocolate soil, the walnut clays, which are the chief productive soil of the valleys of the region.

The grand prairie can be subdivided into four conspicuous areas: 1, a northern or Indian Territory division; 2, a central or Fort Worth division, lying between the Red and Colorado rivers; 3, a southwestern or Edwards division, lying southwest of the Colorado and east of the Pecos; 4, a Stockton division, lying between the Pecos and Trans Pecos mountains.

The Indian Territory division of the Grand Prairie begins at the Arkansas line in the slopes of Little River, where admist the dense forest of the great Atlantic timber belt, with its characteristic flora, small spots of limestone prairie appear with the rich luxuriant grass and peculiar flowers of the Grand Prairie. Going westward the timber belt becomes more and more confined to the alluvial river bottoms, and the spots of Grand Prairie increase the divides of the central streams flowing into the Red River from the north. These prairies strike east and west, and are true dip plains, inclining due south. The plains of the Kiamitia (between Kiamitia and Little River), the Goodland prairie (between the Kiamitia and the Boggy), the Caddo prairie, between the Boggy and the Blue, the Washita prairie, between the Blue and the Washita, and the Marietta prairie, are of this class; that is, they consist of black lands underlaid by the limestones of the Comanche series (the Denison, Fort Worth, Duck Creek, and Goodland beds in the Indian Territory). These plains in the Indian Territory are seldom over 5 or 6 miles wide, and dip southward beneath the lower cross-timber region in which the Red River flows, from the east line of Grayson County to Towson.

The interior border is the descending escarpment overlooking the long and narrow timbered Trinity valley (Upper Cross Timber), a narrow valley extending northward between the plains and the mountains.

An interesting feature of this Indian Territory division is its low latitude, that being some 300 feet below its corresponding Texas portions, owing to its occupying the downthrow of the great northwest and southeast fault extending from Marietta via Preston, Denison, and Bells, Tex., for over 50 miles. By this fault the Indian Territory continuation of the Texas region has dropped down, a fact which has a most important bearing on the artesian question, as will be shown later. West of this fault the strike of the plain and formations changes from due east and west to north and south; also a most important and interesting fact. The continuity of this narrow strip of the Grand Prairie in Indian Territory has been broken by all the through cutting streams, which have wide and deep valleys of the Quaternary terraced, or second bottom type.

The Central or Fort Worth division of the Grand Prairie.—This is the prairie region of central Texas, north of the Colorado, lying between

the two Cross Timbers belts of Texas, as far south as they extend (the lower or eastern to the Brazos), and west of the Black Prairie region between the Brazos and the Colorado. The Missouri, Kansas and Texas Railway from Denison to Austin almost follows its eastern border. The valley of the Upper Cross Timbers forms the western margin south to the Brazos, and thence southeast to Comanche County. From this point southeast to Travis County the margin of the drainage valley of the Colorado forms the line.

From northern Comanche County there extends westward some 200 miles, just north of the thirty-third parallel, a long line of flat-topped buttes and mesas, the drainage divide of the Colorado and Brazos rivers and the remnant of the former westward extent of the Llano Estacado.

The central or Fort Worth division of the Grand Prairie is a typical dip plain or a series of dip plains lying along the descending escarpment of the central denuded region on the west and dipping beneath the ascending escarpment of the Black Prairie (Austin chalk) and Lower Cross Timbers on the east.

The eastern portion of the prairie is comparatively level, like the Indian Territory division, being underlaid by the Washita beds; but as we go westward it becomes more broken, because erosion has worn it down to succeeding lower and lower levels, resulting in some of the most beautiful and characteristic scenery in the country. It consists of wide and fertile valleys, surrounded on all sides by imposing symmetrical buttes of the Comanche Peak type, such as the valleys of Hood, Bosque, Erath, Comanche, Hamilton, Bell, Williamson, Coryell, and Lampasas counties. The buttes and mesas are of white chalky limestone, the Comanche Peak Group of Shumard.

The Southern or Edwards Plateau division of the Grand Prairie.—The Colorado River cuts a very deep cañon through the Grand Prairie, in Travis County, separating the Central or Fort Worth Division from the Southern or Edwards Plateau. The last-mentioned area is that portion of the Grand Prairie south of the Colorado and east of the Pecos, and it differs greatly from the other areas. Its width is greater than its length, and as it lies mostly within the truly arid region it is less adapted to agriculture. Its surface is also more uniform, being composed of hard limestone strata, and is a typical mesa or plateau as distinguished from a dip plain, since its surface, except where it joins the Llano Estacado on the north, terminates on all sides by a descending escarpment instead of dipping beneath some newer formation, as do all the other divisions of the Grand Prairie. In fact, it is but the southeast continuation of the floor of the Great Llano Estacado, from which the Llano beds have been eroded. Hitherto this division has had no specific name, having been usually called "the mountains" from the escarpments which surround it. I now propose for it the name of Edwards Plateau, from Edwards County, where it is greatly developed.

This plateau is an extensive topographic feature and consists of a vast rocky plain of hard limestone, covered by a scrubby growth of mesquite, nopal (Opuntia), and prosopis, or false laurel. It is a good grazing country for sheep, but little adapted to agriculture, except in small patches of creek bottom, owing to the intense dryness of its rocky substructure.

The downthrow eastward of the great fault, which is the cause of the escarpment and which is visible even as far north as Waco, does not become conspicuous until south of the Colorado-Brazos divide, 10 miles north of Austin. From that point southwest to Del Rio, where it crosses

into Mexico, it becomes more and more conspicuous as a great escarpment line, visible to the westward of the International Railway as far south as San Antonio, and from that point westward, north of the Southern Pacific Railway, the direction of the portions mentioned of both of these roads being influenced entirely by it. To this eastward escarpment of the Kerrville Plateau the natives have applied the appropriate name of the Balcones.

So little adapted to agriculture is the summit of the Edwards Plateau that its extent upon the map can almost be traced by the absence of post-offices and other evidences of population.

The northern border of the plateau is marked by the cañon of the Colorado from Austin to Travis Peak and thence by an irregular escarpment running westward through Gillespie, Mason, and Kimble counties, where it turns westward through Menard and McCulloch, forming the boundary of the Llano-Burnet Paleozoic area. It turns westward and southward through Concho and southern Tom Green counties, and thence forms the irregular breaks of the Concho River and is merged into the Llano Estacado in Howard, Martin, and Midland counties. This is a true escarpment of erosion.

An examination of the map will show that the Edwards plateau proper east of Pecos occupies nearly the whole of the counties of Pecos, Edwards, Crockett, Schleicher, Valverde, Bandera, and about one half of the counties of Kinney, Uvalde, Bexar, Hays, Comal, Concho, Tom Green, Irion, Upton, and Crane, and a small portion of Travis. In Upton and Midland counties the plateau becomes the prevalent floor of Llano Estacado, beneath the peculiar formation of which it is found to the northward. Here its narrowest width is found. After crossing this narrow neck for about 50 miles the west escarpment is reached in which are the breaks of the Pecos Valley and which continues southward along that stream to the Rio Grande, forming a valley from 500 to 1,000 feet deep.

The greater part of the summit of the Edwards Plateau, like the Llano Estacado, is void of streams. Its eastern margin, however, is indented by a number of streams which are among the most beautiful in the State of Texas. These streams constitute a natural growth of rivers and usually have enormous cañons in proportion to their volume. They are mostly mountainous towards their head waters, but near the point of emergence from the Balcones escarpment they flow through their own débris in cañons and valleys vastly out of proportion to their present volume, which no doubt represent the former deposition level of the Rio Grande embayment. From the coastward border of the Edwards Plateau flow beautiful streams of water. Although of secondary agricultural value in itself, this vast plateau has a most important bearing upon the water question.

It will be well to observe that there are no sharp topographic or structural barriers between the Edwards Plateau and the Llano Estacado, and that the difference between them is only in the surface formation, the beds of the latter overlapping the former along the thirty-second parallel. Together they constitute a single vast mesa 500 miles long, 280 in width, surrounded on all sides by escarpments, indented by the headwaters of rivers which have their source in the underground drainage from the basal scarps of this vast mesa. While composed of the different foundation strata the Edwards Plateau, topographically and hydrographically, should be considered a portion of the Llano Estacado phenomena. Another interesting fact of the Edwards Plateau is the series of ancient volcanic necks along its southeastern margin, from

Austin to Del Rio, to which I have previously given the name of Shumard Knobs.

The major rivers, the Red, Brazos, Colorado, and Rio Grande, have also deep cut into and almost through the formation underlying the Grand Prairie, and their drainage valleys present the same atmospheric terracing as its western border. In places the river valleys assume the aspect of vertical cañons, as in the Colorado, Pecos, and Rio Grande. The depth of these valleys below the level of the plains increases southwestward from 200 to 700 feet.

The Stockton Plateau.—The fourth and last subdivision of the Grand Prairie lies west of the Pecos, east of the Davis-Chisos mountains, and north of the thirty-second parallel. It is practically a continuation of the Edwards Plateau but is separated from it by the great canon of the Pecos. The northern edge of this area is buried beneath the plains formation, while its southwestern border is faulted and upturned in the mountain blocks of the trans-pecos region and northern Mexico. The area lies almost wholly within Pecos County, a small portion crossing over into Mexico.

For the most part it is a sterile, unwatered district, wholly within the arid region, but much of it can be made available by securing underground water.

The Altitudes of the Grand Prairie.—The Grand Prairie as a rule slopes coastward and increases in altitude interiorward from the gulf. Its altitude above the sea level is least at the extreme northeast corner (the east end of the Indian Territory division), where it is only 500 feet, and is 2,500 feet along the southwestern edge, where it is broken into mountains. The eastern edge is between 500 and 600 feet in height for 300 miles from its beginning in Indian Territory until it makes the southwestern deflection south of Austin. The western edge varies from 1,000 feet at Red River to 3,000 on the Rio Grande. The gradient or slope of the plain can best be understood by the sections and profiles accompanying this volume. It will be seen that it is 14 feet per mile from Red River to Goodland, in Indian Territory; 13.8 feet per mile from Handley to Weatherford through Fort Worth; 13.3 per mile from Waco to Dublin; 34 feet per mile from Georgetown to Burnet; 28.5 feet per mile from Manchaca to the highest points north of Blanco, and 7.8 feet per mile from the later point across the main Edwards Plateau.

From the foregoing data it is evident that the slope of the Grand Prairie averages from its beginning, near the Arkansas-Choctaw line, about 14 feet per mile for 300 miles at the Brazos-Colorado divide it increases to 34 feet per mile. From this point southward the Edwards division shows a steep gradient for a few miles along its eastern border of 28.5 per mile, and upon the summit of the plateau decreases to 8 feet per mile. The ratio of this gradient of the surface to the inclination of the rock sheets is the key to the determination of the artesian possibilities.

The Structure of the Cretaceous Grand Prairies.—All the features described, as well as the water and soils, are the products of the unique geologic structure which underlies the Grand Prairie. This consists of a series of almost horizontal sheets of rock, to which the writer has given the name Comanche series, of different degrees of hardness, endurance, and chemical composition, as well as different capacities for the imbibition and retention of water. It is to the different weathering of these rock sheets, also, that the agricultural soil or rock waste, the variation of forest and the prairie, and other features are due; and hence,

before the water conditions can be understood, the sequences of these rocks and their differences must be understood, although they at first may appear to be similar and unimportant.

This system of rock varies in thickness, as a whole, from 500 feet at its northeastern outcrop to 3,000 feet at the southwestern, the series increasing 3 feet per mile in thickness to the southward. This system of rock sheets can be divided into three conspicuous divisions, which outcrop in parallel belts along its length, the lowest to the westward and the highest to the eastward. They are as follows:

(1) The Washita or eastern and uppermost division;
(2) The middle chalky, or Comanche Peak (Fredericksburg) division;
(3) The Trinity or Basal and western division.

The Trinity or Basal division may be called the great water-retaining division. The Trinity sands do not occur on the prairie proper, but in the valley of its western escarpment. The Comanche or Fredericksburg division is the great escarpment and mesa formation, while the Washita division may be understood as the eastern or dip-plain formation. The Comanche and Washita beds are not water-bearing, but serve as impervious retaining strata.

With these facts in mind let us examine the beds of the divisions a little more in detail.*

THE TRINITY DIVISION.

This is the great water-receiving formation of Texas, and is of the utmost importance in the consideration of the artesian question. These sands may be divided into a basal or sandy and an upper or calcareous division, the Trinity sands proper and the Glen Rose (or alternating beds), respectively.

The Trinity or Upper Cross Timber sands.—While in many places these vary from the underlying floor in material of composition, they are usually composed of fine white cross-bedded sand, locally known as pack sand, mostly unconsolidated, very porous and calcareous, yet sometimes free from lime. In places there are deposits of small jasper and quartz pebbles, seldom exceeding a pigeon egg in size, round and worn, and often cemented by a matrix of iron and lime, sometimes harder than the pebbles. This pebble deposit is of various hues, white, black, and jasper red, and often remains as a residuum over large areas of the red beds and Carboniferous strata, from which the post-Trinity beds have been denuded, as seen in Taylor, Tom Green, Nolan, Montague, and many other counties of the Abilene and gypsum country and along the western margin of the Llano Estacado. Silicified wood and occasional fragments of hard lignite occur, the latter seldom, if ever, in continuous beds or strata, but as if the remnant of some solitary log or tree floated out from shore.

These sands, although higher in altitude than the eastern half of the prairie region, usually occur in a great valley of stratification that border coastward by an ascending escarpment, beneath which they dip (see Upper Cross Timbers). Owing to the unconsolidated pulverulent nature of these sands, they are eroded more rapidly than the adjacent scarp or the underlying floor. As a result of this rapid denudation, the

*The Comanche series has been partially described by the writer and others in several previous papers, for which see American Journal of Science, April and October, 1887; American Geologist, January, February, 1890; Report Geological Survey of Arkansas, Vol. 2, 1888; Report Geologist of Texas, 1890; Bulletin of the Geological Society of America, Vol. 2, 1891.

main area of Trinity exposures north of the Brazos is in a narrow valley, seldom exceeding 10 miles in width, which extends nearly 500 miles irregularly northward from the Brazos to the mountains of Indian Territory, and thence eastward to Murfreesboro, Ark. This valley is bounded coastward in Texas by the escarpment of the more indurated material of the Glen Rose beds, and southward in Indian Territory by the Goodland limestone scarp. The Trinity or Upper Cross Timber Valley is a most marked topographic feature in the Arkansas-Texas region. These sands can be seen in the valley of the Upper Cross Timbers in contact with the underlying Carboniferous and the overlying Glen Rose beds all along the western margin of the Grand Prairie, as at Millsap, Bowie, De Leon, Lampasas, but in places around the immediate perimeter of the Burnet-Llano region. The Paleozoic continent persisted above the Trinity shore line until the Comanche Peak epoch. Fifteen miles south of Burnet, however, in another pre-Trinity topographic valley, now followed by the Colorado River below Smithwick Mills, the lithologic nature of the beds are different. Here they consist of coarser rounded pebbles of Silurian and Carboniferous limestones and Llano schist, as well as quartz from the Burnet granite, and fine cross-bedded sands and shell débris (resembling, as seen at Travis Peak post-office, in the bed of Cow Creek, the Florida coquina). The Trinity beds are there in contact unconformably with hard Carboniferous and Silurian limestones, and contain much débris of the Burnet granite. They also vary in composition and thickness with the irregularities of the floor.

West of the ninety-eighth meridian the Trinity sands are deposited unconformably upon the various beds of the "Permo-Triassic" or red beds, as seen along the base of the remnantal Cretaceous mesas of the Colorado-Brazos divide, Nolan, Taylor, and Mitchell counties. Where the underlying beds are of unconsolidated material, as in the Red River region of northwestern Texas, the remnantal sands often occur over extensive upland areas, as seen east of Abilene, in Taylor County, and in other places. Some of the sand hills along the western escarpment of the plains are also of this nature. This formation, although of limited areal exposure, has a wide range of occurrence along the interior border of the more calcareous beds of the Comanche series from southwestern Arkansas to New Mexico. It is usually absent along the eastern front of the Rocky Mountains, from Las Vegas, N. Mex., northward, unless the Atlantosaurus beds at Canon, Colo., are synchronous, which is not yet known. A portion of the sands of New Mexico described by Marcou and Stevenson, which occur northeast of Santa Fe and at other points near the intersection of the Pecos River, are probably of this formation and may mark its western border. Upon careful comparison I am also inclined to think the white belt of Tucumcari Mesa, New Mexico, and the escarpments of the adjacent Llano Estacado and Las Vegas Raton plateaus is composed of the Trinity sands. Fragmental areas of this terrane are also seen between the Pecos and the escarpment of the Llano Estacado in southeastern New Mexico, east of Eddy, indicating its extent beneath the Tertiary plains. In southern Kansas the Cheyenne sandstones have been ascribed to this age by Cragin.

South of the Colorado and east of the Pecos the occurrence and extent of the sands are concealed by the overlying limestones; and after many journeys in northern Mexico and southern Texas I have been unable to find the base of the Comanche limestones exposed in these regions, except in the vicinity of Miquihuana and Catone, Mexico.

Water conditions.—The imbibing capacity of the pack sands of the

Trinity is very great, for nearly every drop of rainfall upon them is absorbed and transmitted beneath the Grand Prairie, for artesian use. The thickness of the Trinity sands is variable, but from artesian borings at Waco and Fort Worth I estimate it to be from 300 to 500 feet, which together with the known area of the sheet beneath the Grand Prairie of thousands of square miles makes a grand storage reservoir, which saturated with 25 per cent of its volume of water would be equivalent to billions of gallons. While it is doubtful if artesian flow water can be obtained, as a rule, in the area of outcrop of the Trinity sands, there is one well on its eastern margin, Bluff Dale, where there is a small flow. Abundant nonflowing wells are obtainable everywhere throughout the region, however, at shallow depths, and if these are large and deep enough, they can most probably be used for garden irrigation. The northeastern part of the town of Comanche is situated in these sands, and the abundant well water of that place is derived from them.

The Glen Rose beds.—The basal sands of the Trinity division just described are succeeded in continuous depositions by a group of strata which are of great importance to the water question, owing to their great capacity for water. These are composed of soft yellow magnesian fossiliferous beds, sandy at base, alternating in dimension layers with an exceedingly fine argillaceous sand, with occasional layers of porous, chalky, and magnesian limestones and are often oölitic in structure. At Mount Bonnel, west of Austin, this oölitic structure is seen in many of the layers of indurated stones and marls, while nodules and geodes of beautiful anhydrite, calcite, and strontianite crystals are quite abundant and are of value as a means of identifying the terrane.

There are in these beds many layers of dimension stone of almost identical lithologic character with that of the celebrated Caen quarries of France, so largely imported into our northern seaports. This stone is extensively quarried at Weatherford, Granbury, Belton, Oatmanville, Kerville, and other places, and will no doubt some day occupy an important position in the resources of our country.

The unequal weathering of the hard and soft layers produces in the eroded topography a beautiful bench and terrace effect, so much resembling ancient shore lines along the western escarpment of the Grand Prairie, where it overlooks the Trinity Valley and the lower Paleozoic beds from which it has been eroded, that earlier geologists have often confused these features with shore topography. On fresh fracture these rocks are usually white or of an intense orange or yellow color, but weather into a dull gray.

The Glen Rose beds north of the Colorado-Brazos divide are exposed along a narrow area occurring as a prairie strip in the heart of the upper Cross Timbers. Their first appearance northward is in the western part of Wise County, and they increase in area southward in Parker, Hood, Erath, and Comanche counties. They constitute much of Hood, Somerville, Comanche, Lampasas, Ball, Travis, and Burnet counties, occurring in the slopes of the rivers.

These beds do not outcrop in Indian Territory, owing to the overlap of later deposits, but appear in Arkansas from Ultima Thule eastward to Murfreesboro; the limestone layers described in my report on Arkansas under the general classification of the Trinity sands belong to this terrane. In the counties of southwestern Texas, between the Pecos and the Colorado and south of the Burnet-Llano Paleozoic region, these rocks attain a great thickness and form the mass of the

Edwards plateau. The Guadalupe, Comal, Nueces, Frio, Medina, and Devils rivers have their origin in these alternating beds.

They also constitute the prairie spots in the upper Cross Timbers, between Weatherford and Millsap, on the Texas Pacific road, and all the slopes of the valleys, except Comanche Peak, around Gransbury and Somerville. The hills (except the highest summits) around Lampasas, and in Travis County, west of Austin, are familiar examples of these beds. They are beautifully stratified and their rich yellow tints make unique landscapes.*

In the southern area these beds are surmounted by the Walnut clays or Exogyra Texana beds, which are assumed to be the base of the true Cretaceous. North of the Lampasas they are overlaid by the Paluxy sands, an arenaceous, water-bearing terrane of great economic importance hitherto unrecognized and undifferentiated from the Trinity division.

The total area of the outcrop of these beds is large, and they are an important factorin the water question, for they imbibe water for the artesian supply almost as readily as the sands. Upon Mount Bonnel and elsewhere it is noted that immediately after a rainfall the oölitic marls of these beds so completely imbibe the moisture that the roads are made firmer and better for travel instead of becoming muddy.

The thickness of the beds between Comanche Peak and Paluxy is 300 feet, while along the Colorado Cañon they average about 425 feet, as seen in sections accurately measured under my direction by Messrs. Taff and Drake.

It is important to note that these water-bearing beds are merely an upward continuation of the Trinity Sands, enormously increasing the whole thickness and areal extent of the artesian area. The lower Cross Timber sands, on the other hand, are capped directly by very impervious clays, which decrease the downward passage of moisture into them.

The Paluxy sands.—North of the Colorado-Brazos divide the alternating beds of the Trinity division are succeeded by a sheet of fine white pack sand, oxidizing red at the surface, about 100 feet in thickness, closely resembling the Trinity sands and often mistaken for them. They outcrop along the eastern edge of the Brazos Valley, in Parker and Hood, and also in Erath, Comanche, Coryell, and Bosque counties. South of the Colorado-Brazos divide they disappear, the Comanche Peak beds resting directly upon the Glen Rose beds. These beds are especially conspicuous southwest of Granbury, forming the timbered upland of that region, along the line of railroad between Granbury and Stephenville and around the base of Comanche Peak.

The Paluxy sands, which are so called from the town and creek of that name in Somerville County, can first be separated from the Trinity sands in Wise County at a point between Decatur and Alvord. At Decatur the beds are well developed. In general character they are somewhat similar to the Trinity sands, but there are differences. The Paluxy sands have none of the fine pebbles which characterize the base of the Trinity and are more calcareous and argillaceous in places, while those of the Trinity are more ferruginous.

At Decatur the Paluxy sands contain layers of honeycomb bed and very argillaceous limestone. The gradation from the Paluxy to the

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* In the mountains of northern Mexico the beds again appear through the intervening Tertiary plain as a part of the Santa Rosa and Arboles ranges, but they are metamorphosed into a hard blue limestone, which has been mistaken by some for Silurian.

overlying and underlying beds at Decatur is also rather gradual. At Comanche Peak the sands form the plain upon which the butte stands, making a belt of forest region surrounding its base. Here the beds have a thickness of about 100 feet, and of a character similar to that at Decatur. West and south of Comanche Peak they occupy a considerable area, while they extend many miles down the Brazos, finally disappearing at Bluff Mills near Kimball where they make the shoals over which the river runs. Jonesboro, Coryell County, is situated directly on the outcrop of these sands, and the Lanham road northward from the town crosses it several times. A few miles north of Jonesboro the sands have a thickness of only about 15 feet, showing a decrease to the south. The transition from the Paluxy sands to the underlying beds is a little more gradual, for which reason these sands are placed in the Comanche Peak division.

The sand is stratified and occasionally cross bedded, and there are local hardenings. The color varies from gray to yellowish, and the amount of ferrugination which is here found is variable. The sand is also marked by the growth of forest timber, largely post oak, though smaller growths, as sumac, also occur. The sands probably extend for a considerable distance down the Leon Valley, although it is difficult to determine their exact extent on account of confusion with the drift of the Leon River, composed of this débris. The sands appear only in scattered spots further toward the south. Thus, east of Burnet, on the Mahomet road, they appear as occasional areas of reddish sandy lands, bearing a growth of post oak. Sometimes these localities are very small and may be seen on one side of a slight valley of erosion, but not on the other at the same level. Elsewhere, however, they have a very considable and unmistakable outcrop, as, for instance, near the junction of Northern and Russell forks of San Gabriel River.

To the northward the Paluxy sands increase in development, overlapping interiorward the Glen Rose and the Trinity beds and abutting against the mountain area in Indian Territory from a point west of Ardmore eastward to the Arkansas line, where they occupy the escarpment valley of the basal Comanche Peak beds of Preston limestone. They also appear at Preston Bluff near Denison. These sands, which the writer has hitherto classed with the Trinity and which may yet prove to be inseparable from them, have been traced by him during the past year from the Arkansas line westward. At no place in Indian Territory east of the ninety-seventh meridian do the Glen Rose beds outcrop, and it is my opinion that they still remain concealed there by this uneroded overlap of the Paluxy sands, for the alternating beds are again exposed beneath them in Arkansas.

The absence of these sands south of the Colorado-Brazos divide can best be explained on the hypothesis that the near shore sedimentation diminished from the mainland area to the southward and by the existence of the buried pre-Trinity and the pre-Paluxy topographic protuberance of carboniferous limestone, which persisted above the Trinity waters in the Burnet area until the Comanche Peak epoch, and extends from northern Burnet and Llano counties eastward into Lampasas County, and then divides the country into a northern embayment and a southern open sea. The presence of this ridge is shown by the difference of level in the pre Comanche floor, as exposed by the erosion of the Comanche sediments at Lampasas and Burnet, and by the horizontal deposition of the latter upon its unequal altitudes. This is especially well shown in the profile from Burnet to Smithwick-Mills postoffice, the Carboniferous floor being revealed in unconformable contact with the Trinity at all altitudes from 650 to 1,200 feet.

The Paluxy sands are also a water-bearing sheet, and increase the thickness of the water-bearing group (the Trinity, Glen Rose, and Paluxy beds). It is this sand which supplies the first water struck in the Waco and Fort Worth wells. South of the San Gabriel it can not be expected.

The impervious beds of the Comanche Peak and Washita divisions.—The strata succeeding the Paluxy sands are mostly impervious or retaining layers, by aid of which the water in the previously described formations is confined under pressure to greater depths. These sheets in ascending order are as follows:

1. *The Gryphaea rock and Walnut clays.*—The Paluxy sands are everywhere succeeded throughout their extent by a remarkable stratum of oysters (Gryhpaea pitcheri) occurring sometimes in solid masses from 10 to 50 feet thick, and in some places imbedded in a calcareous matrix. This sheet is sometimes underlain and overlain by yellow laminated marls containing a flat oyster (Exogyra texana, Roemer). Hence the Gryphaea rock and Exogyra clays must be discussed as one sheet. The yellow clays also contain occasional flags of hard, crystalline limestone, composed largely of shells of Exogyra texana. For these the name of Walnut clay is proposed, after their characteristic occurrence at Walnut, Bosque County.

At Comanche Peak this great oyster bed and the clays encircle the base of the butte, forming a well-marked bench around the mountain. Below them are the timbered Paluxy sands. The shells are more or less loosely cemented, and form one of the most unique rock sheets in our country. This stratum, which is an invaluable guide to well borers, extends from the Trinity to the Lampasas and is beautifully exposed in the counties of Parker, Wise, Hood, Erath, Comanche, Hamilton, Coryell, Bell, and Lampasas, forming a foundation for the Walnut clays, whose exposure is coincident with it.

The Walnut clays, which are alternating strata of thin limestone flags and yellow clay marls, are accompanied by inconceivable numbers of the flat ear shaped oyster (*Exogyra texana*, Roemer). These clay weather into exceedingly fertile chocolate-colored soil, forming the chief agricultural valleys of the Grand Prairie division. In extent these beds coincide with the Gryphaea breccia. North of the Lampasas they are separated from the Glen Rose beds by the Paluxy sands. South of that river they rest directly upon these sands, and constitute a prominent topographic bench or plain near the summit of the buttes, as seen west of Austin in Travis County.

2. *The Comanche Peak chalk.*—Overlying the walnut clays and succeeding them rather abruptly is more chalky rock sheet, for which Dr. Shumard proposed the name of the Comanche Peak beds. This chalk is the formation constituting the slope of the mountain (butte) between its base of walnut clays and the cap rock. The chalk is hard but readily disintegrates and usually occurs as the slope or escarpment of the buttes and mesas. It is exceedingly fossiliferous and its numerous and characteristic species are given in my check list. The thickness of this bed averages about 100 feet in central Texas, but it thins rapidly to the northward and thickens to the southward. The beds grade upward into the Caprina limestone, from which it is differentiated, however, by displaying more regular and frequent lines of stratification and by its crumbling nature.

The beds are sometimes covered with growth of rather thin scrubby oaks, but usually they are bare, and can be readily distinguished by their whitish slopes, as seen near Ben Brook west of Fort Worth. The

soil is thin or absent, and the angular fragments of the weathering rocks make up the surface. Frequently, however, there are large areas over which the Comanche Peak horizon extends as the surface of the formation.

The Caprina limestone—Topographically this is an important factor in Texas, since its superior hardness and resistance have preserved it as the capstone of the innumerable round "mountains" (buttes), mesas, and plateaus of the central portions of the State, where it forms great rocky plains of resistance to denudation. So perfectly does this limestone find expression in the topography that its extent can readily be traced by the highest contours of the topographic maps of the United States Geological Survey of Coryell, Bell, and other counties. It may be said to be the determining factor in the topography of the region. All the buttes or so-called mountains north of the Colorado are capped by it; the great scarps which often run for miles overlooking the prairies to the west represent the same stream; the walls of the cañons which many of the streams have cut are almost invariably composed of the Caprina limestone. South of the Colorado it is also the cap sheet of the great Edwards plateau.

This rock sheet is the direct continuatian of the Comanche Peak chalk, only the limestone is harder and more persistent, and the fossils less numerous and characterized by the occurrence of a few peculiar forms.

At Comanche Peak the limestone is between 30 and 40 feet thick, and though it increases southward it does not change greatly. It can correctly be called an indurated chalk. It is more or less stratified, although usually a great massive bed from top to bottom. Some parts are harder than others and so make up a curved outline to the bluffs; others are materially softer and frequently are eroded away, leaving either honeycombed cavities or shelves under the overhanging hard layers. In places it contains beds of beautiful flint nodules.

Concerning the distribution of the Caprina limestone it may be said that its outcrop covers an aggregate area larger than the State of Massachusetts. In northwestern Texas the Double Mountains of Stonewall County are capped by the Caprina; as are also Comanche Peak, and all the buttes, and the high bluffs marking the cañon of the Brazos from Bluff Mills near Kimball far down the river, the buttes and mesas about Walnut and Iredell and toward the south, those about Meridian, Jonesboro, and Valley Mills, and the Jehosaphat plateau of Travis County and western Williamson county. It is seen in grand bluffs along the Nolan River at Blum, and in some of the smaller streams near Fort Graham; it outcrops in the creek at Belton, and makes up the whole surface of the broad mesa, extending thence westward for several miles to the point where it makes the cap of the great bluff facing westward—a magnificent illustration of the relations of uniform and gentle dip together with comparative hardness to the process of erosion. It caps the buttes as far west as Kempner and southward toward Florence, where it makes again the level surface of the mesa. Pilot Knob, north of Liberty Hill, Williamson County, and many of the buttes high up the Colorado about Anderson Mills are capped by it. The Caprina terrane is usually covered with a thick growth of scrubby oaks and smaller trees, especially where the outcrop is not of large area and the rock comes near the surface. In places there are broad fertile prairies upon its outcrop, as about Pancake, Bagdad, and Turnersville.

It has been stated that the Caprina is uniform throughout. In the southern portion of its area there is an exception to this rule and it

might be divided into an upper or flinty member and a lower or chalky subdivision. The flints appear in the vicinity of Meridian, but only as a few fragments; they increase very rapidly southward, being seen in grand development about Belton. In the northern part of the region they are comparatively large, oval flattened nodules, usually of black flint. These occur throughout the larger part of the region studied, extending southward at least as far as Pilot Knob, a few miles north of Liberty Hill, and thence on to the Rio Grande, constituting the summit of Edwards Plateau. It is doubtful if the downward extension of this rock sheet be as hard as the surface outcrop, for all the chalky rocks of Texas harden or set upon surface exposure, through their hydraulic properties, and hence in drilling wells this rock sheet will not prove as hard at the surface. This formation thins to the northeast and together with the underlying Comanche Peak chalk and Walnut clays is represented only by a thin stratum in Indian Territory, which is known as the Goodland limestone. (After the town of Goodland in Indian Territory.)

4. *The Washita or Indian Territory Division.*—In order to appreciate this division in the region of its greatest development, we must transfer our attention from central Texas to southern Indian Territory and the Red River, north of Denison. In this region the sands (Paluxy or Trinity) occupy an escarpment valley against the southern flank of the mountains from north of Marietta to Murfreesboro, Ark. These are surmounted on the south by an escarpment of fine white limestone, which I have called the Goodland limestone, and although only 20 feet in thickness it is shown to be the Comanche Peak group. Southward and above this begins a group of strata to which I have given the name of the Washita division of the Comanche series.

This division has its prevalent and characteristic development in northern Choctaw and Chicksaw nations of Indian Territory and in northern Texas, in Grayson, Cooke, and Tarrant counties, where it is the predominant formation. It extends southward to the Rio Grande at Del Rio, but becomes greatly changed in lithologic character, assuming a more calcarous aspect and decreasing in thickness, except a portion of its uppermost beds (the Denison beds), which for water purposes should be classified with the lower cross timbers sands. These Washita beds are mostly impervious, and nonwater-bearing. It is important to be able to recognize them, however, for by them the depth and flow can be estimated with certainty.

5. *The Denison beds.*—The Fort Worth semichalky beds are overlain in the Red River district by a series of shallower deposits of laminated arenaceous clays (the Arietina clays), at the base grading upward into the sandy clays and occasional limestones, the chalky element of all the underlying Comanche series having finally disappeared. The detail of these beds as seen with slight variation in Grayson, Cooke, and Denton counties and in Indian Territory presents a threefold division. At the base they are composed of a blue marly clay weathering brown, with occasional layers of immense rounded fissile indurations, generally brown in color. Above these the beds are more sandy and ferruginous, oxydizing into ironstone and almost indistinguishable from adjacent Dakota sandstones, but separated from them by the uppermost bed of impure yellow limestone which underlies Main street at Denison.

The foregoing rock sheets are those which control the artesian conditions of the central Texas region, and with them in mind the possibility and probability of water can be discussed intelligently. Before doing this, however, a word or two is necessary as to the variation in

character of the extensive deposits. From a study of four parallel sections based upon actual measurements at intervals from 100 to 200 miles, extending from Indian Territory southward to the Rio Grande, the following deductions may be made:

(1) These beds were laid down against the Ouachita Mountain system of Indian Territory and over all the preëxisting area of Texas, except insular mountain areas of the Oregon and Guadalupe mountains.

(2) The more littoral, or water bearing, terranes of the Dakota, Trinity, and Paluxy beds and the Denison beds increase in thickness and water-capacity character to the northward and diminish to the southward.

(3) The chalky terranes, as the Comanche Peak, and Caprina limestone and the Glen Rose beds, thin out to the northeast; they increase enormously in thickness southward, in which direction the open sea prevailed. In boring artesian wells these different thicknesses play an important part.

TOPOGRAPHIC EXPRESSION OF THE COMANCHE TERRANES.

Having described the stratigraphic units which compose the Comanche terranes, attention is invited to the unique topographic forms which characterize them, and to the extensive erosion which they record. Primarily the system, as a whole, may be conceived as a great sheet of strata dipping coastward from the interior at an average rate of 20 feet per mile, coinciding in strike with the shore line against which they were deposited. This strike is first due east and west from Murfreesboro, Ark., to Marietta, Ind. T., a distance of 300 miles. From the latter point it is a little westward of southward to San Antonio, Tex., whence it deflects westward to the Trans-Pecos Mountains. The area of this sheet is marked by two long and simple fault lines, which p oduce the only topographic inequalities due to disturbance. The first of these begins at the angle of the intercepting strike in Indian Territory and Texas, and extends northwestward and southeastward, through a point north of Denison, Tex., for over 50 miles. The downthrow is 600 feet to the northward, and Red River flows along the line of this fault for 20 miles or more. The second great fault extends from near Dallas to Del Rio, Tex., passing by Austin, New Braunfels, and Uvalde, with increasing downthrow as we proceed westward.

There have been at least three great epochs in the destruction and denudation of this ancient Comanche rock sheet. The western border was faulted and much elevated during the northern Mexican, Trans-pecos and southern New Mexican mountain-making epoch, for its rocks enter into their disturbed structure in increasing quantity southward. The sediments of the great Llano Estacado epoch which constitute the Llano Estacado formation, are largely composed of Comanche débris. So extensive was the denudation and erosion of this little-appreciated Neocene epoch that the western two-thirds of the Comanche series was degraded, and entered into the composition of these lake deposits.

That this great denudation of the Comanche series took place since the Eocene is further demonstrated, first, by the utter absence of Comanche débris in the sandy littoral beds of the latter formation; the base leveling of the Eocene time did not cut down to the Comanche series; secondly, by the fact that the Comanche débris again enters into composition of the post-Eocene formations of the coastal region, of probable synchronous age with the Llano Estacado epoch.

The second epoch of destruction of the Comanche series by denuda-

tion thus far recognized was in late Quaternary time, when the Gulf coast coincided with the present western border of the coast prairies. By this process the water-bearing sands were removed from a large area and the older strata exposed.

By this erosion and degradation by far the greater part of this magnificent series has been eliminated, and what now remains, although covering an immense area of country, is only a remnant of the previous extent of these water-bearing rocks.

The present topographic forms of the Grand Prairie can be readily understood. The firm, persistent limestone and harder chalks produce escarpments of stratification. Thus the outcrop of the Goodland limestone in Indian Territory forms an escarpment some 200 miles long, overlooking the valley of the Trinity and Paluxy sands. The Duck Creek, Denison, Fort Worth, and Caprina limestones produce similar landmarks. The softer disintegrated chalks nearly always occur in these places on the slopes or faces of the escarpments, while the clays and sandy terranes, as the Walnut clays and Trinity and Paluxy sands, weather into extensive plains or semivalleys extending interiorward from the escarpments. Where the head-water erosion of the newer drainage above mentioned encroaches upon the shorter and more precipitous drainage slopes of the older and deeper incised drainage, buttes and mesas are evolved. Where the Comanche Peak bed surmounted by the Caprina limestone constitutes the divides it is useless to expect flowing wells. These buttes are invariably of the following types: (1) Flat-topped mesas, surrounded by precipitous escarpments; (2) basal plains or pediments composed of Exogyra texana clays and the Gryphdea beds; (3) slopes of 45° composed of the Comanche Peak chalk. If the divide is composed of the Glen Rose beds the resulting buttes are usually conical, encircled by benches resulting from the alternating soft and hard layers. The great difference of hardness in the respective terranes is also productive. This is especially true of the eastern half of the Grand Plains area of plains that, coincident with the prevailing dip, and terminating eastward against an escarpment of the overlying beds, invariably deflect the drainage parallel to their strike. On the west it is shown by a descending escarpment. These dip plains are beautifully shown in northern Texas and southern Indian Territory, where they constitute the prevalent topography and extend over vast areas. The prairie between Fort Worth and Weatherford is a fine example of dip plain, as well as are all the prairies of north Texas.

WATER CONDITIONS OF THE GRAND AND BLACK PRAIRIES.

These regions, especially the Grand Prairie, possess peculiar water conditions, which are the product of the structural and topographic conditions we have described.

The water features are of three distinct classes, to wit: (1) The Grand Prairie Drainage, or river system; (2) the Mammoth Springs of San Antonio, San Marcos system; (3) the Waco-Fort Worth and the Dallas-Pottsboro artesian systems.

The Rivers of the Grand Prairie.—Two of the great river systems of Texas are found in the Grand and Black prairies, the Red, Colorado Brazos, and Pecos, or rivers of the plains and mountains, cut through them far below the present surface and drain little or none of the surface, as will be seen by examining a map. The second system is one peculiar to the region, consisting of streams which originated upon its surface when the coast line of the Gulf of Mexico almost coincided

Geologic Section and Profile
along the COLORADO RIVER through AUSTIN
from SMITHWICK MILLS, Burnett County
to LITTIG, Bastrop County, TEXAS.
By
ROBERT T. HILL & J. A. TAFF

HORIZONTAL SCALE, 2.5 IN. = 1 MILE.
VERTICAL " , 1 IN. = 1000 FT.

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with the present eastern border of the Grand Prairie south of the Colorado and the east line of the Black Prairie north of that river. Since the emergence of the plain they have been deflected mostly into the streams of the older system.

The Grand Prairie streams are analogous in origin to the small streams that now fringe the coastal plain near the Gulf, and a slight elevation of the coast would leave the latter in the same position as the former. They drained the Grand Prairie when it was a coastal plain, and since its elevation have been cutting deeper and deeper into its surface by erosion and extending their sources westward by head-water erosion. This system of streams is inconspicuous in Indian Territory, and increases in size and importance southward. The central or Fort Worth-Waco division of the Grand Prairie is represented north of the Brazos by the Paluxy and Trinity group; between the Brazos and the Colorado by the Bosques and the Leon; south of the Colorado by the Lampasas and the San Gabriel. The Conchos, the San Saba, and Llano also belong to this group in origin but have cut through the Grand Prairie floor.

The streams of this class having their origin in the eastern edge of the Edwards plateau are the Pedernalis, San Marcos, Guadalupe, Cibilo, Medina, San Antonio, Frio, Hondo, Sabinal, Nueces, Elm, Las Moras, Devils River, and Howards Creek. An interesting fact concerning all of these streams (except the main Trinity, the Concho, San Saba, and Leon, which have completed their head-water journey across the plateau) is that their fall or gradient is much greater than that of the coastward slope of the Grand Prairie. From this feature their valleys become deeper and wider to the eastward, making flowing wells a possibility and leaving large areas of flat-topped divides between them. This simple topographic fact has an important influence in the artesian conditions as will be shown later.

Another interesting feature of many of these streams is that their upper course is composed of arroyos, dry and waterless except in time of storm water. Their medial portions where the stream has cut below the Comanche Peak group are usually fed by springs from the sands and alternating beds; towards their lower portion they often disappear beneath the surface of the limestone débris, pools of water remaining above the ground at short intervals, from which a stream may flow a few feet and then disappear in the rocky débris.

North of the Colorado these streams are of secondary value for irrigation, but south of that river they increase in importance and in the Edwards Plateau are quite extensively used and can be made of great value. In this region the streams cease running (except when augmented by the great springs to be described later), when they reach the level of the great Rio Grande embayment or the Black Prairie plain, being imbibed by the pervious strata.

The Rio Frio is a good example of these rivers. From the point where this stream crosses the Southern Pacific to its mouth it flows in the almost flat, gravel-covered region of the Rio Grande embayment. In this portion of its course, although nearer its mouth, it has little water, often none. Ascending the stream northward it appears to flow from a mountain gorge, but upon closer study these mountains (which are visible to the northward from the Southern Pacific road as far west as Spofford) are seen to be escarpments of the Great Edwards Plateau. Here the river flows through a valley often several miles wide, surrounded by high hills on each side, filled with ancient gravel deposited by the stream when the gulf waters reached into this embayment. The

stream is clear and swift, flowing 1,000 gallons per minute. In a few miles the walls close in and the valley averages 2 miles in width for 15 miles or more, with good agricultural lands in its bottoms.

About 25 miles north of the railroad the precipitous yellow bluffs of the cañon begin to assume higher proportions, and numerous springs begin breaking out of the oölitic marls and sandy clays of the alternating beds. The dip of the strata here is 74 feet per mile. From Van Pelts to Leaky, the county seat of Edwards County, and thence to Frio water hole this great cañon continues, the water generally increasing upstream from the many springs. These springs are very frequent and in the aggregate flow enough water to irrigate thousands of acres. At Frio post-office there are over a thousand acres irrigated from this stream.

From Frio water hole on to the head of the river the water ceases, but the great cañons continue until the rocky summit is reached. Crossing this plateau for a few miles, the head of the south fork of the Guadalupe, descending to the Black Prairie, is reached and the same phenomena are seen, to wit: (1) A long stretch of head-stream arroyos; (2) a medial portion consisting of deep cañons, with widening valleys, where the water becomes abundant and sufficient for magnificent irrigation enterprises, the source of supply being numerous constant springs from the alternating beds which form the walls of the cañon; (3) a lower portion in which the volume decreases through imbibition of the stream débris.

The supply of water for these streams can be clearly seen in the springs in the lower beds of the Edwards Plateau, which flow out at water level and could no doubt be greatly increased in volume by artificial means and preserved for irrigation by suitably lined reservoirs and ditches, which could be constructed with cheapness, because the entire mass of the plateau is composed of rock suitable for making hydraulic cement.

The valleys of the streams of the Edwards Plateau, as the Pedernalis, the Guadalupe, the Comal, Medina, etc., are among the most beautiful, picturesque features of our country, and proper usage of their waters would increase the productivity of the region a thousandfold.

The source of the spring waters which supply these streams is the same as that which supplies the wonderful artesian wells and the mammoth springs of the San Marcos-San Antonio system. Although its surface is an arid country, the Edwards Plateau is a great water reservoir of priceless value to the State of Texas, and the time will soon come when it will be considered criminal to permit one drop of its valuable flow to reach the sea unused.

The streams of the system north of the Colorado are not relatively so important for irrigation, owing to their slighter volume and fall, but by a little care and mechanical aid the capacity of thousands of acres which are now idle or unprofitable could be made more profitable. This is especially true of the Lampasas and Leon, Bosque, and Paluxy.

The mammoth springs of the San Antonio system.—Following the boundary of the Grand and Black Prairie regions of Texas from Dallas to Del Rio, a distance of 400 miles and increasing in volume southward there is a series of most remarkable springs, which rise out of the ground and flow off as veritable rivers. These springs are often of such magnitude and beauty that it is impossible to convey a proper conception of them. They do not break out from bluffs or fall in cascades, but appear as pools often in the level prairie, filled with water of a beautiful blue color which flows swiftly silently away by the outlet which drains them.

The pools are carpeted with exquisite water plants, forming a waving mass in which may be seen many fishes. So transparent and crystalline are these waters, that objects 15 to 20 feet below the surface appear only a foot away. No tint of surface débris or of storm sediment mars the crystal clearness, for they are purified by rising through nature's filter a thousand feet of the earth's strata.

It is an interesting fact to note that the trend or line of these great springs coincide almost exactly with the west edge of the Black Prairie and with the line of the great Austin Del Rio strike fault, which follows its parting with the Grand Prairie. A study of rocks in the vicinity of the springs will always show that there is a system of joints or fractures coinciding with this great fault line and it is up in these fissures that the waters force their way. In other words, these springs have their origin in a deep-seated rock and are forced to the surface by hydrostatic pressure from the basal Comanche series. They are natural artesian wells.

The most conspicuous of these springs are at San Antonio, Del Rio, San Marcos, New Braunfels, and at Austin. In addition to these there are magnificent springs at Round Rock, Georgetown, Salado, Belton, Uvalde, Las Moras, Clark, and other places. The Cedar Springs southeast of Dallas are probably the most northern of the line. There are also numerous small springs of the system which need not be mentioned.

In order to convey an idea of the magnitude of these springs, I shall describe one or two of the most important. Perhaps the largest of the group are the springs at the head of the San Antonio River, a few miles out of the city of San Antonio. They flow out of the ground in great volume, 23,000 gallons per minute, nearly 50,000,000 gallons per day, forming an exquisite lake from which flows through the heart of the city the magnificent river of San Antonio.

Around this marvelous group of springs and upon the banks of its outflow were located the most ancient Indian settlements, or Pueblos, of Texas. The early Spanish missionaries, seeing the beauties of the place and its natural advantages, located six magnificent missions here, within a short distance of one another, with surrounding plantations. The Spanish thus conducted the instruction of the natives, whom they employed in the cultivation of farms and gardens irrigated by the spring waters. The ancient acequas or ditches, followed by the older streets, shape the present outline of the city.

At present the large springs at the head of the river furnish water for the city of 48,000 inhabitants without producing any very appreciable decrease in the outflow in the river, the waters of which are still used to irrigate thousands of acres of gardens and farms, and is sufficient to irrigate many thousands more, although unfortunately most of the water flows to the sea unused.

The springs at Del Rio are, perhaps, the next largest in size. They break out upon the edge of the Edwards plateau, or southern continuation of the Llano Estacado, 2 miles east of Del Rio, and about 5 miles from the Rio Grande. The pool is almost as extensive and beautiful as that at the head of the San Antonio River. From the deep-seated rock at its bottom the water can be seen welling up in a great column, and it has the same peculiar greenish blue of the other streams of this class. No live oaks or other trees surround it, and it stands alone, a great fountain in the desert. From examination of the rocks from which this spring bursts, the Fort Worth limestone, it is seen that they

have the same perpendicular joints and faults found at San Antonio and Austin.

The outflow from the pool, a bold rushing stream, runs off some 5 miles distant to the Rio Grande, which it excels in volume. This spring stream, in addition to running a mill and supplying the village with water, is partially utilized to supply 15 miles of irrigation ditch and irrigate 5,000 acres. The water taken out for the ditches makes no perceptible diminution in the volume of the creek.

The springs of the Comal at New Braunfels are also of this gigantic character and flow off an immense volume of water, which could be utilized for irrigation.

At the village of San Marcos, however, is a large, beautiful, and well-situated spring. It breaks out at the foot of the bluffs of the great fault line and is the source of a beautiful river flowing at least 20,000 gallons per minute. This has long been a famous resort in Texas on account of its beautiful scenery and water. The springs form a lake nearly half a mile long, which overflows into a beautiful stream known as the San Marcos River. At the lower end of the lake a mill and ice factory are run from the water power of this spring, and while no irrigation is conducted there is no reason why this volume of water should not be utilized to irrigate the fertile Black Prairie plain, through which it flows.

In the vicinity of Austin are other groups of artesian springs of remarkable beauty and scientific interest, breaking, along the line of the great fault in which the Colorado flows, from the foot of Mount Bonnel, in the western suburbs of the city, to where it emerges from its cañon of the Grand Prairie region into the broad bottoms of the Black Prairie.

Along this line from the foot of Mount Bonnel to near the mouth of Barton Creek there is a series of springs* pouring up through the great rock joints. Beginning at the north, the chief of these springs is 6 miles north of Austin; Mount Bonnel and Taylor springs are east of the foot of Mount Bonnel; Bee Springs east of the river; Barton Springs and six unnamed springs west of the river. Of these Taylor and Barton springs are the best known. The latter group occur in each side of Barton Creek, near its junction with the river and flow superb volumes of water. A mill is run by the water power from Barton Springs, but it would be impossible to conduct irrigation with the waters owing to their low position relative to the Colorado. The water power which is now mostly wasted should be utilized. These springs are beautifully situated and are the favorite resort of the people of Austin; they are surrounded by pleasing groves of pecan timber and picturesque rocks. Their aggregate volume must reach many thousands of gallons per minute.

Almost due north of Barton Springs, along the same great fissure, and at the low-water level of the Colorado there is another outburst of artesian springs, but owing to the fact that they are at the base of a great bluff and accessible only by boat few people have seen them. This group of springs flows a great volume, but, inasmuch as they break out in the river's edge, it is impossible to gauge them. The aggregate volume of these springs near Austin is so great that the volume of the the river is materially increased by their accession. Equally valuable but of less volume are the springs around Georgetown, Salado,

* These springs unfortunately are all near water level of the river, but they are of great value.

and Belton and they are all of similar origin and nature. The Colorado River and Barton Creek cross this fault line near Austin; hence the occurrence of the springs on both sides of the river.

From the similarity of color, temperature, and occurrence of this great chain of springs, extending half way across the State, there can be no doubt that they are all of similar nature and origin, and that they are underground waters forced up by great hydrostatic pressure through the fissures of the Balcones fault system along the parting of the Black and Grand prairies.

A comparison of their waters and temperature with those of the artesian wells, together with the similarity of the geological structure, leaves no doubt that they have the same origin, the great pervious beds of the Trinity division of the Comanche series which are the foundation of the Grand Prairie, and imbibe the waters at an outcrop at a higher altitude along its western edge.

The volume of water flowing from these springs aggregates many millions of gallons per minute, and since they have never shown any diminution or increase of quantity in seasons of drought or rainfall, these facts are valuable evidence of the vast extent and inexhaustibility of the source of underground water which supplies them and the deeper wells of the Fort Worth-Waco system.

The artesian waters of the Black and Grand prairies.—We have now arrived at the discussion of the greatest artesian belt of Texas, the system of wells found beneath the Grand and Black prairies.

In no portion of the country has there been a grander development of artesian wells than in the past five years in the Grand and Black prairie regions of Texas. At numerous places throughout its extent magnificent flows of water have been secured and what ten years ago was in many places a poorly watered district now abounds in magnificent artesian wells, which supply water to cities and farms in quantity large enough to make many new industries possible, besides furnishing water to irrigate many thousands of acres.

It has been the writer's fortune to observe and encourage this artesian movement from its conception, and in the following pages he proposes to present the underlying principles of the artesian supply, and to point out, as a result of years of study, the areas of possibility and failure and the probable flow obtained, so clearly that wells may be located with certainty.

The artesian waters of this system are so voluminous, and the area over which they can be produced is so extensive that it justly deserves the distinction of being called one of the greatest artesian areas in America—if not in the world—extending as it does, from near Red River, Denton County, to the Rio Grande at Del Rio, a distance of 448 miles in length, and averaging 40 miles in width.

This area over most of which flowing wells can be obtained, is about the size of Minnesota, Nebraska, or North or South Dakota, and equal to the combined area of many of the smaller States, and 22,000 square miles larger than the average State or Territory of the Union, omitting Texas. The area in Texas in which the wells of the Fort Worth system are obtainable, is also greater than the area of any State in the Union, except Arizona, Montana, Nevada, New Mexico, Wyoming, and Kansas.

To deal with such a vast area would be difficult were it not for the great uniformity and similarity of the structure of its geologic features.

The wells vary in depth from 50 to nearly 2,000 feet with every in-

tervening depth. They also vary in volume or flow from less than a gallon a minute to a thousand, and in pressure from nothing to maximum. Although distributed over a wide country, there are many places where these wells can not be obtained, which it is necessary to point out, and many where it can be obtained which are now not known.

The history of this wonderful artesian development is almost too recent to be written, and its development is solely due to the spontaneous enterprise of the citizens who have in every instance except one made the experiment at their own expense. This exceptional instance of State experimentation at Austin on the capitol grounds was not conducted to the fullest extent. Ten years ago a citizen of Fort Worth sunk a shallow artesian well for the purpose of obtaining water for stock. This was secured at a depth of 300 feet. Almost immediately nearly a hundred wells were sunk to the same water level. As is inevitably the rule, the wells stopped at the first water struck, and not until the past year has Fort Worth discovered that her drills had not yet penetrated the lowest and greatest water-bearing strata.

The purity of this artesian supply for domestic purposes and its healthfulness gave Fort Worth an enviable superiority which her rival cities were not slow to imitate, and as a result of her success nearly every city and village in the Grand and Black prairie region and in fact throughout the State, made artesian experiments. A few of these were put down in unfavorable locations and were failures, but hundreds more were successful and to-day most of the cities of the State which before this artesian epoch were without good water are supplied with an abundance.

Wells have been successfully obtained at Fort Worth, Waco, Dallas, Denton, Taylor, Austin, San Antonio, McGregor, Gatesville, Belton, Morgan, Glen Rose, Paluxy, Whitney, and other places which will be enumerated later. Their number and the wide area over which they are found is indicative of a general source and occurrence by which their distribution, value, and possibility can be predicated with considerable certainty. To point out these is the chief object of this paper.

While this development of artesian water in cities was progressing, independent discoveries were being made by the farmers and stock raisers along the western margin of the area, where in certain valleys, like those of the Bosque and Paluxy, shallow wells were struck, and now there are hundreds of these, many of which are used for irrigation and for watering stock.

Counting the aggregate water of the great artesian wells and artesian spring rivers, there is flowing from the underlying rock sheets of this region at least 300,000 gallons of purest water per minute, 1,800,000 per hour, or 41,200,000 gallons per day, a volume as large as many notable rivers.

When it is considered that the first water was experimentally reached only twelve years ago, and the greater underlying sheets only four years ago, the future possibilities are beyond estimate.

Availability of the water sheets of the Black and Grand prairies.—In order to fully understand the laws of these wells it is necessary first to thoroughly study the simple stratigraphic arrangement of the rock sheets of the region, which can be best understood by reference to the cross-section profiles and maps accompanying this paper. Typical cross sections and profiles of the Black and Grand prairie regions are given extending from the interior coastward. From an examination of these it will be seen that the general structure consists of the sheets described

on previous pages, inclining coastward at a small angle only slightly greater than the topographic slope, which, as asserted in the introductory chapters of this paper, constitute the ideal conditions for transmission of artesian water. These rock sheets have different capacity for imbibition and transmission of water. The more porous ones are water bearing; their capacity is not only proportionate to its facilities for imbibition and transmission, but its area of outcrop.

Water-bearing strata.	Thickness.	Retaining or nonwater-bearing strata.
	Feet.	
8. The Navarro or Glauconitic sands..	300	
		7. The Taylor marls. The Austin chalk. The Eagle Ford clays.
6. The Lower Cross Timber or Denison sands.	100	
		8. The Washita division, Fort Worth limestone, Duck Creek chalk, Kiamitia clays. 4. The Comanche Peak division, the Caprina limestone, the Comanche Peak chalk, the Walnut clays.
3. The Paluxy sands....................	100	
2. Portions of the Glen Rose beds...... The Trinity sands.	700	Portions of the Glen Rose beds.

The water-bearing strata.—Of the water-bearing strata above mentioned the Glauconitic sands, which occur along the eastern border of the Black Prairie, can not be considered in the discussion of the prairie region, for any wells penetrating to them would be in the regions to the eastward. Omitting these (the Glauconitic or Navarro sands) from consideration, there are five great water-bearing sheets of the section, separated by impervious layers, as follows:

4. The Lower Cross Timbers, or Denison (in part) and Dakota sands.
3. The Paluxy sands.
2. Portions of the Glen Rose beds.
1. The Trinity sands or Upper Cross Timber sands.

Each of these sheets outcrop in characteristic area, and incline to the eastward at a slightly greater angle than the average of the topographic slope beneath the overlying beds, transmitting the water under hydrostatic pressure to lower depths. Each sheet has great differences in thickness, extent, capacity for imbibing waters and for transmission; also in chemical composition which affects the quality of the water. The exposed area or outcrop of the water-bearing sheet constitutes the receiving area for the stratum which receives the rainfall. The continuation of the receiving rock sheet beneath the overlying beds constitutes the water-bearing sheet.

Now it is evident, since they incline eastward beneath the overlying sheets, that these strata get deeper and deeper into the earth to the eastward and are overlaid by more rock sheets; so that the Trinity sands which constitute the surface of the Upper Cross Timber Valley in part, between Millsap (altitude 822) and Weatherford (altitude 1,000), average 1,000 feet above sea level. At Fort Worth, 28 miles east of Weatherford, they are only 280 feet above sea level; at Dallas, 58 miles east, they are 960 feet below sea level, or 1,566 feet from the surface, and so on as we go eastward, estimating that these strata incline at the rate of 28 feet per mile.

The Paluxy sands which outcrop just west of Weatherford and around the base of Comanche Peak are 1,400 feet above the sea; at Fort Worth

200 feet above the sea (or 300 feet below the Trinity River level, and 590 below Tuckers Hill), at Dallas they are 800 feet below the sea, and at Terrell 2,300 feet below sea level, or 3,100 feet below the surface.

The Lower Cross Timber sands (which do not outcrop west of Fort Worth) are the surface formations between Arlington and Handy. They are from 731 to 800 feet below Dallas, and at Terrell 2,475 feet, the dip, about 45 feet per mile, being slightly greater than that of the Trinity sands.

Not only do these rock sheets become deeper and deeper to the eastward, but they are successively covered by other rock sheets which must be drilled through. While a drill upon the western edge would begin in these Terrell sands, which are there the surface formations, on the eastern margin of the Black Prairie the drill must penetrate the entire thickness of the two Cretaceous formations to reach the lowest water beds of the Trinity, or between 3,500 and 4,000 feet, as at Terrell, Greenville, Corsicana, Marlin, and Thorndale.

A drill at Greenville, Terrel, Kaufman, Corsicana, Thorndale, Marlin, or any other point along the eastern margin, would be obliged to penetrate all the formations, including the five water beds, to reach the Trinity sands. A similar drill-hole well in the main Black Prairie, as at Mesquite, Waxahachie, Hubbard, Temple, Taylor, or Manor, would not penetrate as many rock sheets by the thickness of the Ponderosa marls and Glauconitic beds to the east. A drill in the Austin-Dallas chalk would penetrate fewer strata by the thickness of the Ponderosa marls, and one in the Eagle Ford shales still less. Drill holes sunk in the Black Prairie, Lower Cross Timber sands, or the Grand Prairie, go through respectively less thicknesses to the westward until finally a well in the western margin of the Upper Cross Timbers gets the same water at the surface in ordinary surface wells without artesian flow. A well drilled west of the Trinity sands can not possibly obtain water from any of the sheets of the coastward incline, for they do not occur west of that line.

By a study of the maps and profiles it will also be evident that the entire set of water-bearing sheets underlie all of the country east of the Lower Cross Timbers north of the Brazos, although some of them may be practically unavailable through great depth or high altitude of the drilling station. Between the Lower Cross Timbers, and the Paluxy sands, *i. e.*, the eastern margin of the Upper Cross Timbers, all the water-bearing sheets will be available, except that of the Dakota or Lower Cross Timber sands, for the latter does not extend over the region west of the Missouri, Kansas and Texas Railway, except in northern Johnson County, but has been worn away by erosion.

In the portion of the Grand Prairie west of the Paluxy sands or south of where they disappear by thinning out, a drill will start geologically below the three upper water beds and penetrate only two sets of water strata—the Trinity and alternating beds, as in the wells at Glen Rose, Iredell, and Pidcocks Ranche. Finally, in the eastern margin of the Trinity sands the well will only penetrate the Trinity sands as at Bluff Dale and Paluxy. In all of these cases the general rule is maintained, that the depth of any rock sheet in the series decreases to the westward until it ceases by outcrop.

Geologically speaking, it might be said that nature has done much to help the driller, for wherever a rock sheet is cut through by a stream or entirely removed by erosion the artesian engineer has that much less to drill through.

By this process of erosion it will be seen that the well at Terrell, al-

though 2,200* feet deep, has not yet penetrated to the rock at Dallas, which occurs at the surface, owing to the removal by erosion at Dallas of the strata through which the well at Terrell has been drilled.

The citizens of Dallas are 2,200 feet nearer the Trinity water sheet, but their wells, averaging 800 feet deep, do not reach the Fort Worth limestone, upon which the latter city has erected its drill derricks, and are still 1,500 to 2,000 feet above the great Waco supply. Nature has removed for Fort Worth not only the total thickness penetrated by the Terrell well (2,200 feet) plus that of the Dallas well (750 feet), but also the Lower Cross Timber sands (plus 200 feet) from which Dallas receives her water supply, and brought Fort Worth 3,000 feet deeper or nearer than Terrell to the main Trinity supply.

Finally the Fort Worth drills until the past year have not penetrated below the Paluxy sands, and hence not to the strata upon which Glen Rose is situated, so that nature has removed by erosion for the people of the latter place the whole thickness of rocks represented by the Fort Worth well placed on top the Glen Rose, plus that of the Dallas wells on the Fort Worth, plus the Terrell wells on top the Dallas, or nearly 3,500 feet of strata.

It is evident to those who have followed the statement of the stratigraphic and topographic conditions of the regions that the numerous artesian wells flow from the four great rock sheets, those of the Lower Cross Timber sands, the Paluxy sands, the various sandy and öolitic beds of Glen Rose, and the Trinity of Upper Cross Timber sands. The Glen Rose and Trinity beds occur in such close proximity and merge into each other so closely, that they will be discussed as one water-bearing group averaging 700 feet in thickness, from which Waco secures her "Jumbo" flow.

Each of these water-bearing beds has been penetrated by well borings. I shall discuss the receiving and available areas of each sheet.

The Dallas-Pottsboro Group of the Black Prairie region, or the artesian wells of the Lower Cross Timber (*Dakota*) *flow.*—The flowing artesian wells of Pottsboro, Denison, and Dallas, and the nonflowing artesian wells of Sherman, Paris, and Midlothian, a north and south belt of country extending from Denison, near the Red River, to near the Brazos, all have their origin in the sandy strata of the Lower Cross Tim-

* Section of drill hole at Terrell, Tex., with continuation of rock sheet to be penetrated:

Glauconite beds	Soil	15	
	Joint clay	31	
	Rock	10	
	Sand	20	
			76
Ponderosa marls	Shales and clay	185	
	Soft rock	10	
	Blue shale	340	
	Rock	8	
	Blue shale	484	
	Rock	8	
	Blue shale	600	
			1,607
Austin chalk	Solid rock		195
	Lignite		12
	Lime rock		195
End of drill hole			2,200
Eagle Ford shale			525
Lower Cross Timber sand or first water at about			100
			2,800

bers, which constitute the receiving area of the Dallas-Pottsboro flowing wells, as will be shown by the following evidence:

Within a circumference of 2 miles of Pottsboro (alt. 769), in Grayson County, situated in the medial beds of the Eagle Ford clays, four wells were bored which struck a flow 250 feet from the surface in the Lower Cross Timber sands, which outcrop a few miles west and northwest at a higher altitude. These wells are estimated to flow 25,600 gallons per day and are of magnificent volume and pressure.

In drilling them no chalky strata were struck, inasmuch as they commenced geologically below the Dallas chalk, the lowest limestone of the Black Prairie region, and did not reach to the highest limestones of the Comanche series, but found water in the Lower Cross Timber sands. At Sherman (alt. 747), some 20 miles southeast, situated geologically on rock sheets higher (on the base of the Austin-Dallas chalk), a well was drilled 632 feet through the Eagle Ford clays and into the Lower Cross Timber sands, from which the water rose to within 100 feet of the surface, but did not flow, probably on account of the slight pressure and leakage of water from the sheet at its outcrop near Cook's Springs and other points north of the city, and possibly because the sands were not penetrated deep enough.

At Dallas (alt. 436 to 500 feet), some 70 miles south of Sherman, and on the same rock sheet (the Austin-Dallas chalk), but some 300 feet lower in altitude, numerous wells have been struck in the top of the Lower Cross Timber sands, at depths (varying with the altitude of the surface and penetration of the sands) from 672 to 800 feet. All of these struck water in the Lower Cross Timber sand beds which outcrop from 15 to 25 miles west of the city, furnishing in most instances an abundant supply. There are apparently several veins of water, owing to the fact that the Lower Cross Timber sands have many clay beds alternating with them, the first being at 632 feet and another at 734 feet. Until about one year ago only the upper waters, with a very weak flow, had been struck, but the county and city authorities combined sunk a deeper well on the public square, which produced about 200,000 gallons daily. Since that time others have been struck, notably at the Exall building, the McLeod hotel, the Cockrell building, and at the office of the Dallas News. The last was a most characteristic enterprise of that paper, and through the courtesy of Mr. Doremus, its editor, I am enabled to present an illustration, which will convey an idea of the appearance of the Dallas well.

A section of the newspaper well illustrates the character of the strata passed through at Dallas, and by comparison with those at Waco and Fort Worth and Austin, it will be seen that the latter go into strata entirely different and below those penetrated at Dallas. A similar comparison with the Terrell drill record, 30 miles east, will show that the latter has not yet reached the water sands, although 2,200 feet have been passed.

Every foot of the stratification penetrated by the drill can be plainly seen outcropping on the surface between Dallas and Handy stations, 23 miles west, on the Texas Pacific road. (See profile 1.) The sand and gravel first penetrated is the old terrace deposit of the Trinity Valley, on which Dallas is built. This can be seen resting on the white limestone (No. 3) or Austin-Dallas chalk in various parts of the city. This chalk is exposed in the bluffs of the river at the Texas Pacific bridge, and is the cliff formation of the suburb of Oak Cliffs. In the bluffs of Mountain Creek, which follows the escarpment valley of the Austin chalk from Oak Cliffs to its head, can be seen the clays (No. 2) as well as on the surface of the Black Hog-wallow Prairie, extending

westward to the Lower Cross Timbers; the latter begin about 18 miles west of Dallas, where the upper layers, from which Dallas secures her water, are exposed, thus giving the strata an inclination of about 45 feet to the mile towards Dallas, as can be measured in the bluffs of chalk south of Eagle Ford. Notwithstanding the wonderful simplicity of the stratification there are many people in Dallas who attribute all kinds of remote origins to these waters, as the Rocky Mountains, 1,000 miles west; while one leading citizen has traced them across the great Ouachita Mountains, in Arkansas, to the Ozark Mountains, in Missouri. He says: "My idea is that the source of the artesian supply here is in the Ozark Mountains, in southern Missouri and northern Arkansas. It is not in the northwest, for if it were Fort Worth would have an immense supply of artesian water, whereas it is limited to the first light flow that we have struck," etc. This opinion had hardly been delivered when Fort Worth exploded his Ozark hypothesis by penetrating the basal Trinity flow and obtaining unlimited water.

The fact that flowing wells are obtained at Arlington (altitude 613), in the eastern edge of the Cross Timbers, from these sands at depths from 30 to 150 feet is corroborative proof of the fact that they supply Dallas, and from the fact that they have sufficient pressure to flow at this altitude of 613 feet it may safely be assumed that artesian water from the same Lower Cross Timber sands can be struck (unless there is some unknown disturbance in the strata east of Dallas) at all points in Dallas County, whose altitudes are less than 613 feet and at a depth to be estimated by multiplying the distance in miles to the east margin of the Upper Cross Timbers by 50, the approximate inclination in feet of the strata per mile,* and subtracting from the total the difference in altitude. Thus at Mesquite (altitude 509), 30 miles east of Arlington, the eastern margin of the Cross Timbers or receiving area, the depth of the water may be approximately estimated as follows: $(30 \times 50)-(618-509)=1,500-109=1,491$; and at Terrel (altitude 514), 50 miles east of the Lower Cross Timbers, the Lower Cross Timber sands would be approximately: $(50 \times 50)-(618-514)=2,500-104=2,396$; at Grand Prairie (altitude 500 feet), 7 miles east of Arlington, the water would be: $(7 \times 50)-(618-500)=350-118=232$ feet.

At Midlothian, southwest of Dallas, 25 miles in Ellis County, is another experiment in the Lower Cross Timber sands, but the well was not bored deep enough into them, and the water is of poor quality. It rises to within 30 feet of the surface.

Section of well at Midlothian:

	Feet.
Austin chalk and soil	24
Eagle Ford calcareous clay shales	234
Light yellow sandstone	20
Total	278

It is evident by comparing the Dallas section that this Midlothian well has not yet reached the main stratum of sands, but should penetrate at least 250 feet more of clays. The wells at Sherman, Dallas, and Midlothian are about the same distance from the outcrop of the Cross Timbers, and all begin in the same stratum, the Austin-Dallas chalk.

Near the eastern margin of the Lower Cross Timbers is another line of experiments from which we can learn much, to wit, at West Denison

* This inclination may be more or less by a few feet, as it is impossible to determine it more accurately in the clay.

and Pottsboro, near the northern margin, at Arlington, west of Dallas, and at Files Valley, in Hill County, west of Midlothian. The magnificent flow of the Pottsboro wells has already been described. At Arlington there are many wells which overflow. They vary in depth from 15 to 120 feet, and begin and continue in the sands. At Files Valley (altitude 460 feet), in Hill County, just east of the Cross Timbers, J. R. Lane has bored 123 feet through the basal Eagle Ford shales and Upper Cross Timber sands, striking a small flow of 3 gallons per minute.

This line of wells at Denison, Pottsboro, Arlington, and Files Valley, although I should like more evidence, indicates by the outcrop that the Lower Cross Timber water supply decreases southward because the receiving beds thin out in that direction.

In the region between the Brazos and Pottsboro, the capacity of the Lower Cross Timber sands for water is shown by the fact that wherever dug into they yield water. Numerous surface wells occur throughout their extent, as well as springs, as Cooks Springs, near Denison, which flow from them. At Denison these sands have been literally mined for their water of saturation by the water company which supplies the city, an interesting method of procuring underground water from the rock structure. A large area southwest of the city is underlaid by an extensive sheet of the porous ferruginous Lower Cross Timber sandstone of great imbibing and transmitting capacity. A vertical well 25 feet in diameter was sunk from which a lateral tunnel was run into the sandstone, parallel to its bedding. The percolation soon filled this tunnel and well, constituting a complete reservoir, from which the water is pumped through the city.

This is an ideal method of utilizing the water of saturation, inasmuch as it exposes to free percolation by the walls of the tunnel a vastly larger surface of saturated strata than could be secured by a vertical shaft or well. This method of obtaining water is worthy of consideration elsewhere.

These tunnels at Denison show that the Lower Cross timber sands are completely saturated with water below the line of evaporation, which is about 25 feet in this region, judging from the average depth of surface wells.

The waterworks company at Denison has also recently drilled three wells into these sands and secured a fine flow of 20,000 gallons per day, each at a depth of 200 feet. The area of Grayson County in which these wells can be obtained, however, does not extend north of Main street in Denison, nor into the eastern part of the city, as has been proven by experiment.

The total area of the Lower Cross Timber sands in Texas, from Red River to Waco, as carefully mapped out by my directions, is 794 square miles. The average rainfall is 36 inches per annum over this area. Of this amount at least 50 per cent is imbibed and becomes the source of artesian water.

Extent of the Dallas, or Lower Cross Timber artesian area.—According to the well known hydrostatic law that water will not rise above its level, it is evident that artesian wells can not be expected from the Lower Cross Timber sands except at points to the eastward of their western margin and at a lower altitude.

The altitudes of the Lower Cross Timber sands, between the northwest corner of Grayson County and the Brazos River, are as follows:

East edge.	Feet.	West edge.	Feet.
South Denison	712	Dexter	850
Lewisville	485	Denton	711
Arlington	616	Roanoke	656
Alvarado	700	Handy	750
Vaughin	550	Cleburne	800
		Whitney	650

Comparison of these altitudes, shows the average of the eastern edge to be 600 feet and of the western edge 736 feet. Since the white rock cliffs, of the Austin-Dallas chalk to the east average 750 feet, except where cut into by drainage as at Dallas, it is evident that the area where a flow well is possible will be (1) the country of the Eagle Ford clay prairies in Grayson, Collin, Denton, Dallas, Tarrant, Hill, and Johnson counties, which lie between the escarpment of the White Rock and the Cross Timbers. (2) The eastern edge of the Cross Timbers themselves. (3) The valley of the Trinity River, an area of at least 1,000 square miles. From the geographic distribution of the formations the depth of the wells in these areas can not exceed 900 feet on the east and 35 feet in the west. A fourth possible area is the eastern belt of the Black Prairie as at Greenville, Terrel, Kaufman, and Corsicana, where these sands may be struck at a depth greater than 2,200 feet, and good negative or nonflowing wells obtained.

Owing to the absence of the sands south of the Brazos division, they furnish no water in that region, and hence the wells at Waco and Austin although beginning in the Austin-Dallas chalk, as at Dallas and Sherman, do not get any water until the Paluxy and Trinity sands are reached.

In the Dallas chalk or White Rock region it is highly improbable that flowing wells from the Lower Cross Timber source can be struck except in the drainage valleys, like that of the Trinity, and it is hardly probable that the water of the Dallas wells will ever be exhausted by artificial means, provided too many wells are not drilled in close proximity, in which case the water would be drawn faster than it could percolate through the strata.

Negative or nonflowing wells in which the water rises near the surface, like the well at Sherman, can be obtained from these sands over most of the Black Prairie, their depth increasing to the eastward.

The value of these nonflowing wells should not be underestimated, for by simple mechanical means, as windmills and engines, no more expensive than the present cost of water, a supply of good, pure, nonmalarial water can be obtained for the villages and farms throughout the Black Prairie region, as well as sufficient in many places for garden irrigation.

The value of the Lower Cross Timber waters for irrigating purposes is a subject which promises great future results, especially in the extent of the Cross Timber proper, where the sandy soils, although at present devoted to unprofitable cotton-planting, are admirably suited for fruit-growing and will ultimately be entirely devoted to a more refined branch of agriculture.

The supply of underground water, although it will have to be raised by mechanical means, will be necessary to make this industry possible.

In the following chapters it will be seen that the other great sheets of artesian water are still below the Lower Cross Timber sands of the Dallas-Pottsboro area and will also supply water to this region.

THE WELLS OF THE FORT WORTH-WACO BELT OR TRINITY SYSTEM.

It must be evident that the wells west of the Lower Cross Timber sands south of where they disappear, as at Fort Worth and at Waco, can not possibly receive their waters from the same source as those of the Dallas-Pottsboro area, but must receive them from the higher region toward the west.

There are nearly 1,000 wells supplied from these sands in the belt of country between the main line of the Missouri, Kansas and Texas Railway, from Whitesboro to Taylor and Austin, and the Upper Cross Timbers, and the region is capable of supplying many thousand more without materially or perceptibly diminishing the supply, except in minor instances which I shall point out.

It is not everywhere that these wells can be obtained, however, as I shall point out in the following pages; laws of depth, occurrence, and distribution will be given which, if observed, will be of inestimable value to the people of this region.

The shallow flows of the Fort Worth system or wells of the Paluxy Sands supply.—The first successful wells in the Grand Prairie region were drilled at Fort Worth, in the river valley (altitude 490), and struck moderate flows of water at 263 feet in the western edge of the city and 484 feet below the highlands (altitude 662).

Over a hundred of these shallow wells were bored, and, as the stratum from which they were obtained, the Paluxy sands, was the thinnest of all the water-bearing sheets and had the smallest receiving area, these wells soon ceased to flow and it became necessary to pump them.

Before passing to the deeper supply beneath Fort Worth, it is important to add a few words concerning this first or shallower water derived from the Paluxy sands. Wells were drilled into this not only at Fort Worth, but as far north as Denton (altitude 628 feet) and as far east as Hearsts Fishing Lake, 10 miles southeast, developing an area of 30 miles square in which that water can be struck. The surface stratum in all these cases was the Fort Worth limestone of the Washita division, which is at least geologically lower by 1,000 feet than the Austin-Dallas chalk at Dallas and 600 feet lower than the same rock at Waco, and hence drills have that much less thickness in penetrating to it. The Eagle Ford clays here decrease in thickness southward and the Lower Cross Timber sands thin out at Waco, hence the difference between the chalk and Fort Worth beds there.

By the following section of a well at Kellers, northeast of Fort Worth (here given because it is the most complete record accessible), the exact strata penetrated will be seen:

		Feet.
Fort Worth Beds	Yellow clay	30
	Blue marl (soapstone)	2
	White limestone	49
	Blue marl	24
	White limestone	40
Caprina limestone	White limestone	95
Comanche Peak beds	Blue soapstone	42
	White limestone	52
	Blue soapstone	5
	White limestone	34
	Blue soapstone	5
	White limestone	5
	Blue soapstone	7
	Oyster-shell rock (Gryphæa)	13
Paluxy sand	Brown sand rock	13
	White sand rock	14
		400

It will be seen that the water is struck in the sands below the great Gryphæa (oyster) bed at the base of the Comanche Peak group, which are the Paluxy sands of the above section and are the same sands which can be seen outcropping between Cresson and the Brazos, at Weatherford, and elsewhere west of the city. By reference to the measured section of Comanche Peak, Hood County, it will also be seen that this is the first and thinnest sheet of water-bearing sands of the Trinity group.

The following sections will illustrate four other wells of Fort Worth:

	No. 1.	No. 2.	No. 3.	No. 4.
	Feet.	*Feet.*	*Feet.*	*Feet.*
Altitude of surface	629	5	490	662
Rock sheet at surface	....	....	....	....
Limestone and marly clays of Fort Worth, the Washita division	115	....	....	....
Duck Creek and Kiamitia	88	....	....	....
Chalky limestone and Caprina limestone	95	370	155	....
Marls of the Comanche group, Comanche Peak	150	....	....	....
Oyster-shell rock (Gryphæa breccia)	13	22	25	....
Paluxy sands, bearing best water	27	55	62	425
Totaldepth of first flow	488	447	242	425

Well No. 1 was bored deeper, striking water at 805, 1,030, 1,085 and 1,300 feet. At the latter depth it entered the impervious clays of the carboniferous system, with occasional sand, and is now nearly 4,000 feet in depth.

The first water was obtained in the Paluxy or highest sands of the great water-bearing series, the extent and distribution of which can be seen on the map. This is the sand into which the citizens of Weatherford dug for their surface water, and can be seen on the bluffs of the creeks around that city, and as far east as Aledo Station.

In the Waco wells a flow is usually found at 1,100 feet, which may also come from the Paluxy sands, but, owing to absence of sufficient data, this can not be verified, although the areal outcrop of Paluxy sands is quite large in Hood County, also in Bosque and Hamilton, where it can be recognized as the upland post-oak sandy region; its thickness decreases southward, and it is doubtful if it is valuable for water-bearing purposes there. Owing to its excessive mineral character and its relative depth, I am inclined to think the first flow at Waco is from the upper magnesian layers of the Glen Rose or alternating beds.

Wells have also been obtained from the Paluxy sands as follows:

Place.	Altitude.	Surface beds.	Depth.
	Feet.		*Feet.*
Denton	628	Denison beds	600
Hursts Lake	450	......do	500
Packery, 3 miles north of Fort Worth	500	Basal Washita	....
Shooneners, 3 miles west of Fort Worth	....	......do	....
Baur survey, 9 miles southwes ; Van Ostrand survey, 5 miles northwest.	....	......do	....
Watson survey, 5 miles southeast	....	Denison	....
Rightley's, 10 miles west of north	....	Basal Washita	....
G. B. Stanley's survey, 4 miles northeast; Keller's, northeast.	....	....do	....

There is but little doubt that this water can be obtained over all the Grand Prairie in Tarrant County wherever the altitude is less than 900 feet; this includes all of the creek and river bottoms in the county,

and all the upland prairie and Lower Cross Timbers in the eastern half of the county. The depth will not exceed 600 feet at the eastern edge of the area and decreases 28 feet in depth per mile to the westward.

These sands also underlie the Dallas Pottsboro area at a depth of about 600 feet below the bottom of the Lower Cross Timbers water, which thickness equals that of the Washita and Comanche Peak impervious beds.

Value of the Paluxy water for irrigation.—This water can be used for irrigating hundreds of small farms and gardens in the eastern edge of the Grand Prairie region, but improper application has created a strong prejudice against it. The mode of using has been to sprinkle the growing plants with water instead of soaking the soils. The chemical ingredients of the water are said to be injurious to the leaves, but Prof. J. P. Stelle, agricultural editor of the Fort Worth Gazette, has shown it is harmless and fertilizing if applied to the roots.

The value of these wells to the stock-raising industry, however, is incalculable, and their discovery and use to the region in which they occur has been many millions of dollars in value.

It would be improvident to stop a well in the Paluxy Sands, however, for, as will be shown in the succeeding pages, they are but the beginning of a much more abundant and valuable supply that everywhere underlies them.

THE DEEPER FLOWS OF THE FORT WORTH-WACO SYSTEM.

When it was known that Fort Worth's drills had only tapped the first sheet of the great series of water strata extending 700 feet deeper the rumor was spread and is still believed by many that Fort Worth's artesian supply is limited and decreasing. When Waco had demonstrated the existence of deeper beds and voluminous wells in the system, Fort Worth, with the wonderful enterprise characteristic of that city, began an experimental well on the highest hill in the city, which not only fully demonstrated the existence of at least far greater water strata, but went completely through the water-bearing series and penetrated over 2,300 feet of impervious clays underlying it.

In February, 1890, the city council contracted for the sinking of an experimental well, determining to fully test the possibilities of the artesian water supply for the city waterworks use. The experimental well was located at about the highest point in the city, the top of Tuckers Hill, 52 feet above the Main-street crossing of the Texas Pacific tracks and 42 feet above the court-house square.

In boring this well a fine stream of artesian water, which flows 170 gallons per minute with a pressure of 15 pounds per square inch, was struck at 900 feet. This was cased off and the boring continued to a depth of 1,035 feet, when a stream of 200 gallons per minute was struck, which flowed with a pressure of 21 pounds per square inch. This stream was in turn cased off, and the work proceeded until at 1,127 feet still another fine artesian vein was pierced. This flowed to the surface 245 gallons per minute with a pressure of 29 pounds to the square inch.

All of these flows could have been put together, when they would have discharged fully 500 gallons per minute, or 720,000 per day, and at a point 142 feet above the Trinity River. This last flow not having the pressure sufficient to carry it to a standpipe 100 feet high, was cased off, and the boring continued in search of a still stronger flow.

Flowing Wells at Waw, Texas.

This experimental well has now been drilled to nearly 2,800 feet in depth, and it is proposed to continue it to a limit of about 3,000 feet, we believe, if more water is not reached short of that depth. Now, as a result of this experimental work, three heavy veins of artesian water have been located as underlying the city, the least of which will raise water to a height of 40 feet above the highest point in the city, and the deepest of which will raise water to a height of 61 feet above the highest point in the city. This remarkable discovery has been further demonstrated.

First, the Texas Brewery, whose location is 50 feet lower than Tuckers Hill, sank their well to the first or top artesian vein and obtained a flow of upwards of 240 gallons per minute, with a pressure which carries the water to the top of their immense building 90 feet above the ground. Encouraged by this success, the packing-house company began a well at their house on the north side at a point 120 feet lower than the top of Tuckers Hill, and it has now been drilled through the first and second artesian veins, and it is flowing at a rate of over 800,000 gallons in twenty-four hours. They will continue the well to and through the lower artesian vein, when the flow will (if the Tucker Hill discoveries hold good for the north part of the city) be fully 1,500,000 gallons in twenty-four hours. The packing-house well is undoubtedly now flowing more water in twenty-four hours than any other artesian well in the State of Texas by at least one-third, and when the third artesian vein is reached it will be the "Jumbo," the geyser well of the State. The city experiment has demonstrated that Fort Worth has the artesian water in quantities sufficient to supply a city of 1,000,000 people should occasion ever require it. Ten wells located down in the valley, above high-water mark, will supply over 10,000,000 gallons of pure artesian water each twenty-four hours, and the water is pure; there is no mineral of any kind in solution in it; it is as clear as a diamond, as pure as melted snow. Surely if there is an artesian city in Texas, it is Fort Worth.

While to Fort Worth's enterprise the credit is due for first discovering the underground water supply of the Grand Prairie region, it was the citizens of Waco who developed its greatest capacity, by first boring deep below the Paluxy sands into the great water-bearing sheets of the Trinity sands.

Two years ago (1889) a water company of Waco* struck the first successful well on the higher ground in the south of the city, striking several flows of water, the volume of which was so great (estimated at from 500,000 to 1,000,000 gallons per day) that it created great rejoicing and has been the cause of untold value in the development and improvement of the industrial and hygienic conditions of that city.

The discovery of this flow immediately led to the drilling of other wells, and as a result the city and vicinity possesses numerous superb wells, flowing an aggregate of many million gallons per day, and supplying water not only for all public and domestic purposes, but power for various industries, such as clothing factories, wood-working machinery, and irrigation.

The wells vary in altitude from 400 feet (Kellum's, north of the city) to 550 feet (Prather's, 6 miles southeast), and have an average depth of 1,886 feet, or about 1,160 feet below the sea level. The water is hot, having a temperature of 103°, and is soft and tasteless.

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*Waco, altitude 431–500, is situated on the banks of the Brazos River (altitude 400), and south of the city the country rises to the general level of the Black Prairie. The surface, except where covered by terrace deposits of the rivers, is the Austin-Dallas chalk.

The success of these wells at Waco gave great impulse to artesian experimentation, and since their discovery flows have been struck in the same beds at Austin, Taylor, Belton, Temple, and Fort Worth, but of varying pressure, volume, and temperature, owing to difference in altitude and initial stratum.

The number and characteristics of these wells can best be presented by the following statement, furnished me by Maj. S. H. Pope, of the board of trade, and through the kindness of Mayor C. C. McCulloch:

WACO BOARD OF TRADE,
Waco, Tex., July 7, 1891.

DEAR SIR: Replying to your esteemed favor as regards the artesian wells in and around Waco, will say that there are now eleven overflowing and two approaching completion.

Seven of the flowing wells and one nearing completion, now about 1,700 feet deep, are owned by the Bell Water Company. One of the flowing wells and one nearing completion, now about 1,000 feet deep, are owned by the Waco Light and Power Company. The three remaining flowing wells belong one to each, respectively, to the estate of W. R. Kellum, deceased, William L. Prather, and Tom Padgett.

The altitude of the public square of Waco is 421 feet above sea level. The altitude, diameter, depth, estimated flow, temperature, and initial pressure per square foot of the several wells are as follows:

Name of well.	Altitude.	Diameter.	Depth.	Flow per diem.	Temperature.	Initial pressure.
	Feet.	*Inches.*	*Feet.*	*Gallons.*	° F.	*Pounds.*
The Moore Well	493	6	1,840	600,000	103	*60
The Bell Well †	500	6	1,820	500,000	102½	*60
Jumbo Well No. 1†	500	8	1,848	1,200,000	103	‡60
Jumbo Well, No. 2†	500	8	1,860	1,000,000	103	60
The Glenwood	495	8	1,860	1,000,000	103	*65
The Dickey Well	532	8	1,840	1,000,000	103	*60
The Bagby Well	475	8	1,845	1,000,000	103	*60
The Waco Light and Water Power Company Well	532	6	1,812	300,000	100	40
The Prather Well	655	6	1,607	500,000	97	‡40
The Kellum Well	420	6	1,776	1,000,000	105	‡76
The Padgett Well	485	6	1,886	1,000,000	....	‡72

*Estimated. †These three, the Bell, Jumbo No. 1 and No. 2, are 50 feet equidistant. ‡Tested.

The foregoing statements of flow per diem (twenty-four hours) are estimates. An attempt was made to measure the flow of Jumbo No. 1, but it was unsuccessful. An expert, a member of the United States Artesian Survey Corps, who made the attempt and failed, estimated the flow at 1,000 gallons per minute. If this statement is correct the output per diem would be 1,440,000 gallons.

I have assumed the output of this well to be 1,200,000; with this as a basis the output of the other wells has been estimated. The pressure of the Jumbo, Prather, and Padgitt wells have been testified; the temperature of all has been ascertained by the thermometer.

The first well overflowed in March, 1889, and the last in May, 1891. Neither has affected the flow of the other, although 6 are located on Bell Hill and 3 on Dickey Hill. The distance between the Prather and Kellum wells is about 4 miles.

The analysis of the waters of the Bell well, made by the leading chemist of Chicago, in grains per United States gallon, is as follows: Silica, 1.3456; alumina, trace; iron sesquioxide, 1.493; sodium chloride, 6.0267; sodium potassium sulphates, 23.9583; calcium sulphate, .0000; sodium carbonate and bicarbonate, 20.6597; magnesian carbonate, .8432; calcium carbonate, 1.1579. Total solids by calculation, 53.8201. There is no appreciable difference in the taste of the waters of any of the wells; therefore we must assume that this one analysis covers all.

The average depth of the wells within the city limits is 1,842 feet. The average depth of all, including the Prather and the Kellum wells, is 1,814 feet. I inclose a written report of the Padgitt well, prepared by Mr. P. J. Fishback, the contractor. He is a practical well-borer and something of a geologist. I think this report can be received as a fair statement for all the wells in the city. I send by mail 5 bottles of sand passed through.

The water is soft, and is used for drinking, cooking, bathing, washing—in a word, for all domestic purposes. It is also used for sprinkling flowers and lawns. It has not been used extensively for irrigation, but so far has proved very healthful to all vegetation.

It is applied to motors of from 2 to 15 horse power. These motors run fans, printing presses, all the machinery of a coffin factory, with a daily capacity of 100 coffins; also a clothing factory of 250 sewing machines, cutters, and other necessary machines. I regret that I can not furnish you photographs of the interior factories. You have photos of the group of 3 wells.

I am, yours truly,

S. H. POPE,
Secretary.

The rock sheets passed through in boring these wells, from a section kindly furnished by Mr. Fishback, who kept an admirable record of the Padgitt well, are as follows:

Record of drilling in Padgitt artesian well, Waco, Tex.

1. Dark soil, changing to light, calcareous .... feet.. 18
2. Soft white limestone, "Austin-Dallas chalk" .... do... 110
3. Blue shales, "joint clays" .... do... 162
4. Light-brown, carbonaceous shales .... do... 40

These shales gave a small quantity of petroleum. They slaked rapidly on exposure to air and water, and soon became fine mud. Walls of well caved badly in this stratum.

5. Brown calcareous marl .... feet.. 15
6. Blue shales, "joint clays" .... do... 121
7. Brown, carbonaceous shales, lignitic in character .... do... 60

These shales gave off a small quantity of petroleum. Walls of well caved badly in this stratum, necessitating the setting of 7⅝-inch casing just below, in stratum of marl.

8. Brown calcareous marl .... feet.. 38
   The 7⅝-inch casing was set in this marl at .... do... 536
9. Blue shales, "joint clays" (Washita) .... do... 411
10. Brown carbonaceous shales, lignitic in character .... do... 45

These shales gave a trace of petroleum. They caved badly, drilling proceeding through and beneath them with much difficulty.

11. Cream-colored, calcareous marl .... feet.. 156

Immediately under the last carbonaceous shale stratum and in the upper portion of this marl stratum, considerable water came in.

This water was highly charged with impurities of lime, sulphur, iron, and probably epsom salts. Water was not analyzed. The 5⅝-inch casing was extended to the bottom of this marl stratum to shut off this impure water, which was done, the hole being dry for the next 75 feet. The 5⅝-inch casing was set at 1,176 feet.

12. White limestones were occasionally interstratified with thin seams of blue shale, or light-colored calcareous marl (Washita and Comanche Peak), feet. 554

From about 1,250 feet to 1,500 feet water came at different horizons, making an artesian flow of considerable volume; below 1,500 feet apparently no more water came in until the first water and sand were reached, at 1,782 feet.

13. Blue calcareous, silicious shales .... feet.. 30

These shales were of somewhat plastic natures, contained some lime, with also considerable proportion of very fine, light blue sand. This stratum would seem to mark the transition from shallower and more agitated waters, depositing sand, to deeper and more tranquil sea conditions, favorable to the growth of shellfish and the making of limestones.

14. Soft, very fine-grained, gray sandstone (Trinity) .... feet.. 15

This sand was seemingly dry, producing no apparent increase in the volume of upper water.

15. Red, plastic shale, local bed in Trinity .... feet.. 7
16. Soft, very fine-grained, light-gray sandstone ....

This sand responded with water as soon as reached, and gave the first strong artesian flow proper from the well.

17. Blue shale, local bed in Trinity .... feet.. 5
18. Soft, very fine-grained, light-colored sandstone ....

This sand largely increased the flow of water.

19. Blue, plastic shale, local bed in Trinity .... feet.. 8
20. Soft, very fine-grained, white sandstone .... do... 28

In this sand the largest volume of water was obtained, slightly increasing the pressure and temperature and nearly doubling the flow from the well.

21. Blue, plasic shale .... feet.. 5

The thickness of this stratum unknown. This shale was drilled into a depth of five feet, but the flow and pressure of water was so great that the sand pump would not descend through the lower flow of water, and, consequently, the sediment could not be removed from the bottom of the well below the horizon where the heavy flow of water came in, and drilling had to be suspended.

Further drilling could only be prosecuted by shutting out the flow of water by extending a string of casing to the bottom of the well and reducing the size of the well below that point.

Pressure of well	pounds..	72
Temperature	° F..	103½
Volume, per diem (approximately)	gallons..	1,000,000
Total depth of well	feet..	1,866

Remarks.—While no opinions on matters of this nature can ever be accepted as absolutely correct until verified by the drill, yet from the grained texture, quality, and appearance of the sands, I am decidedly of the opinion that the bottom of the sandstone column has not yet been reached in the Waco wells, and that there is strong probability that other and coarser sands may be found still deeper. If found, they would give yet an increased volume of water, with also slight additional pressure and temperature.

Very respectfully,

P. J. FISHBACK,
Contractor.

Reviewing the foregoing section (the Padgitt well at Waco), the formations passed through are as follows:

Altitude.	Depth.	Thickness.	Remarks.
285–357	0–128	128	Austin chalk and residual soil.
357–79	564	436	3, 4, 5, 6, Eagle Ford clays, fish beds.
79 above to 631 below sea level.	962	398	8, 9, 10, various beds Washita division marly clays, with limestone.
636 to 1,255 below sea level	1,250	....	First water near top of alternating beds.
	1,742	778	11, 12, Caprina, Comanche Peak, Walnut clays, and alternating beds into Trinity.
1,353–3 below sea level	1,838	98	13, 14, 15, 16, 17, 18, 19, 20, 21, Trinity sands, with its clay bands, 98 feet.
Total	....	1,838	
Total thickness of water-bearing group.	....	538	

From a study of this section and a comparison with those of Dallas and Fort Worth it is evident that the total thickness is about the same as if the Dallas drill hole (Nos. 1–6 of the Waco) should be placed on top of the Fort Worth (Nos. 7–21), of the Waco section.

It will also be evident that neither the Lower Cross Timber sands, from which Dallas obtained her supply, or the Paluxy sand, which should be between Nos. 6 and 7 and Nos. 12 and 13, respectively, are sufficiently developed, if at all, to be noticeable, and that Waco draws her main supply from an entirely lower and different source, the 876 feet of strata below the horizon of the Paluxy sands, and especially the lowest 98 feet of sands. This, the greatest of the flows, is 1,278 feet below the bottom of the Dallas wells.

The following section, measured from the top of Comanche Peak to the Brazos River, where that stream has exposed by erosion the lower

half of the rock of the Waco drill hole, will give a view of these water-bearing strata:

Section from Brazos River, altitude 755, *at Granbury, to top of Comanche Peak Butte, altitude* 1,250, *showing detail of lower water-bearing beds of Comanche series.*

	Feet.
7. Caprina—Hard, chalky limestone, character uniform throughout; fossil shell rudistes occurring very irregularly; forms caprock of mountain; impervious	33
6. Comanche Peak beds—Slightly softer chalky limestone; more variable in hardness than the Carpina, thus forming distinct benches; impervious	66
5. Gryphæa and Walnut beds—Hard limestone (small fossil; gryphæa pitcheri, above it)	3
Marls, calcareous, with Gryphæa	8
Local harder layer intervening	1
Marls with Gryphæa	4
Rough broken limestone	1
Marls, upper part chalky	15
Hard crystalline limestone walnut slabs, with Gryphæa, marly layers	4
Hard yellow limestone	1
Marly layer	5
Hard limestone flags, lower portion more fossiliferous and argillaceous and pervious to water	3
Marly layer	12
Marly layer	3½
Limestone slabs	1
B. Limestone slabs, compact and coarser	½
Marly layer	4
Limestone slabs	2
C. Marly layer	3
Compact magnesian limestone slabs	1
Marly layer	4
Hard white crystalline limestone makes decided bench	3
Marly layer	10
Gray, slightly argillaceous limestone	1
Marly layer	4
White broken limestone, fossiliferous	2
Three soft limestone layers, with intervening marls	6
White, evenly laminated limestone, with ferruginous segregations	1
Calcareous marl, changing gradually into harder limestone	8
Soft argillaceous limestone (pervious) surface	1
Angular, broken up with blocks, clays more argillaceous and marly at upper portion, basal portion more arenaceous and laminated	21
Rough, broken argillaceous limestone (porous)	2
Gryphæa marls and clays with white calcareous hardening	4
Marls	5
Massive breccia of Gryphæa	4
Marls with many Grypaea	15
Gryphæa	9
Hard Gryphæa layer	1
Marls	4
Local harder layer	1
Marls	3
Limestone with Gryphæas	4
Marls, Gryphæa and Exogyra texana	4
Local hard layer	1
Marls with Gryphæas	14
4. *Paluxy water sands.*—Forest clad, in portions somewhat calcareous but usually constant throughout	100
3. *Alternating or Glen Rose beds.*—Slightly fossiliferous above, sandy below	4
Hard magnesian limestone, few fossils, small, ferruginous segregations	4
Soft marl	10
Oyster beds	4
Marly beds	3
Hardened limestone layers	3
Marly beds	10
Caprotina, caprotina limestone; caprotina very abundant at base, upper portion less fossiliferous, rather variable lithologically	201

1. Sand, with some limestone and sandstone layers and calcareous nodular layers.

Résumé of Comanche Peak sections.

		Feet.
4. Comanche Peak division, 220 feet	Caprotina limestone	33
	Comanche Peak chalk	99
	Walnut clays	32
	G. Pitcheri beds	56
3. Paluxy sands		100
2. Alternating or magnesian beds above Glen Rose horizon		175
3. Glen Rose or alternating beds and Trinity sands here pierced by drills at Glen Rose, about		300
Total thickness of water-bearing group		795

These basal sands are the great Trinity sands, the most extensive and porous water-bearing sheet in our country, except perhaps the Dakota sandstone in Dakota, while the alternating beds above them are full of small sandy layers, which in other artesian regions than this, where they are so overshadowed, would in themselves be esteemed of great importance, and which tend to increase the capacity of the wells bored through them. These alternating or Glen Rose beds (chalk, oölites, and sands) all possess great imbibing and transmitting powers, so that they increase the receiving area of the Trinity sands. This condition of the overlying beds is quite different from that of the Lower Cross Timber and Paluxy sands, each of which, it will be remembered, is overlaid immediately by a dense impervious clay layer.

The outcrop of catchment area of the water-bearing Trinity division (Trinity sands and alternating beds) constitutes the surface formation of a vast area in Montague, Wise, Parker, Hood, Erath, Somerville, Comanche, Brown, Mills, Lampasas, and Burnet counties north of the Colorado, having an outcrop covering a total area of many square miles. The water-bearing sheets of the Trinity group aggregrate from 538 feet, as at Waco, to 750 feet at Fort Worth, and underlie the whole of the Grand and Black prairies, an area of 78,000 square miles, becoming deeper relative to mean sea level at the rate of about 45 feet per mile to the eastward. This vast sheet of porous sand is thoroughly charged with water, and constitutes a great underground reservoir which holds in constant saturation at least many billion gallons of water, under strong hydrostatic pressure. The imbibing capacity of the Trinity sands is the maximum, owing to their angularity, coarseness, and purity, as can be seen by the rapid manner in which the sands imbibe the water.

These sands, from which Waco secures her water, are the same pack sands which furnish the ordinary well water in the town of Comanche (see profile 2). Twenty-two miles east at Dublin they have dipped beneath the surface 400 feet lower than the altitude of Comanche (altitude 1,000), and so on at Whitney, McGregor, and other places to Waco (altitude 421), where they are 2,400 feet lower than at Comanche, and at Marlin, on the east of the Black Prairie, they will be at least 3,000 feet.

Many other successful wells of the Waco type have been drilled, beginning in the Austin chalk horizon, as at Waco, or in the lower beds of the overlying Ponderosa marls at Temple and Taylor. The first well at Austin, drilled by the State in the capitol grounds, was stopped contrary to expert advice at the first weak flow, and is practically valueless. Two other wells north of the capitol, one at the State asylum and the other a private enterprise, were drilled into the deeper and to the greater flow, which, owing to the superior altitude of Austin, however, (some 150 feet above Waco) have not so great pressure.

These experimental wells, which form a continuous chain from Fort Worth to Austin, with the single exception of a few miles, leave the conclusion that the flow from the Trinity sands can be procured the entire distance, 180 miles, both in highlands and valleys, along the line of the Missouri Pacific road, and many miles on each side, at least as far west on the uplands as McGregor and Belton.

These wells also prove the great distribution and approximate uniformity of the underground sheet of Trinity sands, and the city of Dallas, which is situated like Waco and Austin, upon the chalk, instead of being content with the present supply, should bore to this greater flow.

THE WESTERN VALLEY WELLS OF THE GRAND PRAIRIE, OR THE SHALLOW WELLS OF THE TRINITY FLOW.

The western edge of the Grand Prairie, as has been explained, is cut across by its rivers at various intervals into deep drainage valleys, often 500 feet deep, which have left the remnant of the plateau standing as the flat-topped divides and mesas as so often seen in Hood, Erath, Comanche, Bosque, Hamilton, Coryell, and Lampasas counties. These uninhabited mesas are usually capped by the hard, sterile Caprina limestone, while the wide valleys between them are occupied by the fertile soils of the Walnut clays or rich stream alluvium, upon which is seated all the agricultural population of the region. In some of these valleys, as that of the Paluxy in Somerville County, the Trinity in Parker, and the Cowhouse in Lampasas, is a remarkable series of numerous shallow, flowing artesian wells, which have been inexpensively drilled by the farmers. This system of shallow wells has been principally developed in the valleys of the Paluxy and Squaw creeks, in Somerville County, and at Pidcock Ranch, 100 miles south, in Lampasas County.

In the former locality there are nearly 200 flowing wells, varying in depth from 30 to 300 feet, all of which begin in the various horizons of the Glen Rose, or Alternating Beds below the Paluxy sands and reach into the Trinity sands.

These wells can best be seen at Glen Rose, in the valley of Paluxy River, near where it flows into the Brazos, and from there into that stream some 20 miles to Bluff Dale, in Erath County. Nearly every farmer has one or more of these flowing wells, which are used for domestic purposes, stock-raising, and, in many cases, for irrigation. They vary in flow from 10 gallons per minute to 300, the smaller flows usually being from small bores and wells which do not reach the main supply. Nearly every house in the town of Glen Rose is supplied with one or more of these wells.

The water from the shallower wells is usually charged with mineral from the strata of the Glen Rose Beds. It has been the rule that this mineral water, which is the same struck in the Upper Beds of the whole Trinity division, as at Waco, Georgetown, Pidcock Ranch, can be cased off and a better flow obtained by going to the deeper and purer sands.

The finest of the wells seen by me was that at Mr. Lanham's farm, 6 miles west of Glen Rose, which flowed an 8-inch stream and about 350 gallons per minute, with which he abundantly irrigated about 50 acres of corn, cotton, and cane. I was informed upon good authority that there were many more farms irrigated in the same way. At Paluxy a similar well is used for irrigating a field of cotton. The total area of the Paluxy Valley from Bluff Dale to its mouth and of Squaw Creek, where this series of wells are obtainable, is over 200 square miles.

Over the southern drainage divide, in the valley of the Bosque River, a companion stream of the Paluxy, in Erath and Bosque counties, there is another similar area of shallow wells, as at Iredell and westward, having the characteristics of the Glen Rose group.

A similar area exists in the valley of the Leon, the next stream southward, from Gatesville westward. This stream valley should be thoroughly tested.

The next stream valley southward is the Cowhouse, and here again there has been in the vicinity of Pidcoke's ranch another great development similar to that around Glen Rose.

The following account from Mr. Roessler's excellent report will give a good idea of these wells:

Coryell County.—W. H. Belcher, Pidcock Ranch post-office: In Cowhouse Valley, through which runs a small river, part in Hamilton County and part in Coryell County, are about 50 flowing wells. One well flows 50 gallons per minute, and it is about 320 feet deep.

The other wells stop at the first stratum of flowing water. I believe if the wells were 100 feet deeper they all would run from 50 to 57 gallons per minute. These wells are all mineral water, but it has never been analyzed. None of these wells have more than 30 feet casing, and I expect that there is a great waste of water through the strata of these rocks. These wells can be drilled here for $200. Mine was the first drilled by insurance. Its depth is 290 feet; cost $500; capacity 2½ gallons per minute, and is used for household purposes, live stock, and for irrigating a small garden, and is good for beets, potatoes, cabbage, corn, tomatoes, etc. It could be stored, but it is not. Altitude, 2,500 feet; rainfall about 30 or 35 inches. J. T. Meeks's well, 252 feet deep, cost $200; L. McCloskey, King post-office, well, 240 feet deep; cost $240; flow 2 gallons per minute; used for household purposes and live stock. Not good on vegetation. J. M. Davidson, Pecan Grove; flowing well, 220 feet deep; cost $233.60; flows one-eighth inch stream, soda and sulphur, good for family use, watering stock, and irrigating one-fourth acre of garden. Affects fine vegetables. Flowing wells are from 130 feet to 600 feet; rainfall about 35 or 36 inches, and beautiful showing for irrigation.

I have heard of no drilling in the upper valleys of the Lampasas, San Gabriel, and Colorado, but they present exactly similar conditions, as has been proven in part by the 500 to 1,000 foot wells procured in the lower valleys of the Lampasas and San Gabriel at Belton and Georgetown.

North of Glen Rose the continuity of these shallow conditions has been demonstrated at Springtown, in northern Parker County, where, according to Roessler, there are six or seven flowing wells within a radius of 2 miles at Springtown, Parker County, and this seems to be the only point in the county where such have been obtained. Water is generally obtained in ordinary wells at a depth of 18 to 40 feet. The rainfall is given as follows: 1878, 31.34 inches; 1879, 23.71 inches; 1881, 23.54 inches; generally sufficient to mature crops every year. The western half of the country is somewhat hilly, and is to a large extent covered with post-oak timber. The subsoil in many places is stiff red clay, and is usually found in such localities where it could be used in the construction of storage "tanks" or reservoirs from 1 to 10 acres in extent. Compared with irrigated lands the people of this county get a "half crop" from year to year. They could vastly improve on this by using the facilities they have at hand.

There is but little doubt that these wells can be procured in the valleys of the western edge of the Grand Prairie, in Parker County, west of the Grand Prairie escarpment, and in the valley of the Brazos near Granbury.

There are similar conditions in the lower valley of the Edwards Plateau, such as the Frio, New Braunfels and other rivers.

The total area developed of these valley wells of less than 500 feet

depth is over 2,400 miles square. The system has only commenced its development.

Irrigation with these shallow wells has been demonstrated by farmers of the Paluxy Valley to be both practicable, inexpensive, and profitable.

In a former report I have shown that the region is subject to serious droughts, whlie the average yield is small, running from one-quarter to one-half a bale of cotton per acre. Most of this superb flow of water is not utilized for irrigation, because the methods and benefits of irrigation are not understood. Farmers, however, have attained good results from irrigation. Mr. William Lanham, who lives 6 miles west of Glen Rose, has an 8-inch well which flows about 400,000 gallons of freestone water per day. With this he abundantly irrigates 30 acres of land, utilizing the water only a few days in the year. Although he came to Texas from more humid regions and had never before seen irrigation, his success has been great. He has confined his efforts to the least profitable irrigable crops, corn, cotton, and Louisiana sugar cane, and has never manured or otherwise fertilized his land. The following table shows his experience:

Products.	Average yield without irrigation.	Yield of same land irrigated.		
		1888.	1889.	1890.
Corn ....bushels..	25	75	66	40
Seed cotton ....pounds..	200 to 500	2, 200	3, 000	4, 000
Molasses of Louisiana or Ribbon cane..........gallons..	....	....	350	350

Several other experiments in irrigation in the same neighborhood have met with equally successful results. No one has irrigated alfalfa, clover, small grains, or small fruits, which are most susceptible to profitable irrigation.

At Paluxy village, 10 miles west, were two irrigated farms upon which cotton was growing two bales to an acre.

In general, however, the waste of this water is most unfortunate, for if properly used it would be of priceless value to the agricultural interests of Texas.

THE FIVE HUNDRED-FOOT TO ONE THOUSAND-FOOT WELLS OF THE TRINITY FLOW, OR THE MORGAN-GATESVILLE GROUP.

Still further eastward and down these valleys in the belt usually having a surface of the Morgan clays, there is another belt of wells which are deeper, owing to the accession of overlying strata layers and dip to the eastward. These are secured around Morgan, Meridian, Georgetown, Belton, and other places in a north and south belt, of the Grand Prairie, upon the outcrop of the Comanche Peak and Washita divisions, and the wells average from 500 to 1,200 feet deep. This belt includes the Fort Worth and Denton wells, those at Whitney, Georgetown, McGregor, and Belton, and especially fine flows have recently been struck at the last two places, both of which are situated upon or near the base of the Washita division (Nos. 8, 9, 10 of the Waco section). At McGregor the well is 1,200 feet deep and has the great flow of the Waco wells (19 miles east). The shallow Paluxy flow had been obtained here several years ago upon the farm of Col. W. P. Gaines. At Belton (altitude, 519), situated at the top of the Caprina limestone, a little lower geologically than Fort Worth or McGregor, two

superb flows have been struck this year, concerning which Mr. Wilson T. Davidson, the young geologist of that city, has furnished me the following list:

Note on wells of Belton by Wilson Davidson.—There are two wells within this place, both drilled within the past twelve months, 1890–'91. One of these in the jail yard near the court-house (approximated altitude, 519), presents the following section, as furnished by the well-driller:

			Feet.
1.	Soft limestone	Comanche	25
	Blue marl or slate		300
2.	Blue limestone	Glen Rose	50
	White putty or mud		15
	White limestone (soft)		50
	Sand rock with iron pyrites (hard)		10
	Limestone		100
	White mud		25
	White limestone		250
	White mud		25
3.	Sandstone	Trinity	40
	Total		890

The flow is very strong, but as its amount had not been taken I could not get it.

The citizen well dug some months ago is 70 feet higher than this, and (according to Col. Denny) this one is approximately 70 feet less in depth.

The water in the county well is 30° F. warmer than the well dug last march (Col. Denny).

As to the flow of the new artesian well—by making repeated experiments with a large barrel, and stop watch, I found it to be 1,002,040 gallons per day. The barrel was filled in five seconds every time. Of course this is not exactly correct, but approximate. I also wish to state that the water sand is 35 feet in thickness, same as in the other well.

The Fort Worth drills commence in 8 and penetrate to 12, to reach the Paluxy water, and from thence downward the section is similar to Waco.

Owing to the lower geological horizon of all these places, they are 500 feet nearer to the great water sheets than the Austin-Waco belt, by the absence of thickness of the Austin chalk in part and the Eagle Ford clays (the Lower Cross Timber sands missing at Waco).

THE LIMITS OF THE FORT WORTH-WACO SYSTEM.

It requires but a simple calculation of dip and altitude to see that the inclination of the lowest water-bearing sheets will carry them to a depth beyond practical reach (2,500–3,000) for economic use. This limit, if we estimate the thickness of the rock sheets, will be found in the eastern belt of the Black Prairie region, between the great Atlantic Timber belt and the line of outcrop of the Austin-Dallas chalk. At Thorndale (altitude, 450) and Terrel (altitude, 425–514) situated upon a north and south line, some 200 miles apart, upon the eastern margin of the Black Prairie, at the top of the Ponderosa marls, over 2,000 feet have been drilled into these marls without reaching the Austin chalk, and it is probable that the same conditions prevail every foot of the way between them, as illustrated about half way, at Marlin (altitude 394) Falls County, where the drill is now 1,600 feet in the marls.* Wells at Kaufman, Corsicana,

* The first or Paluxy flow has since been struck at 2,100 feet in the Marlin well.

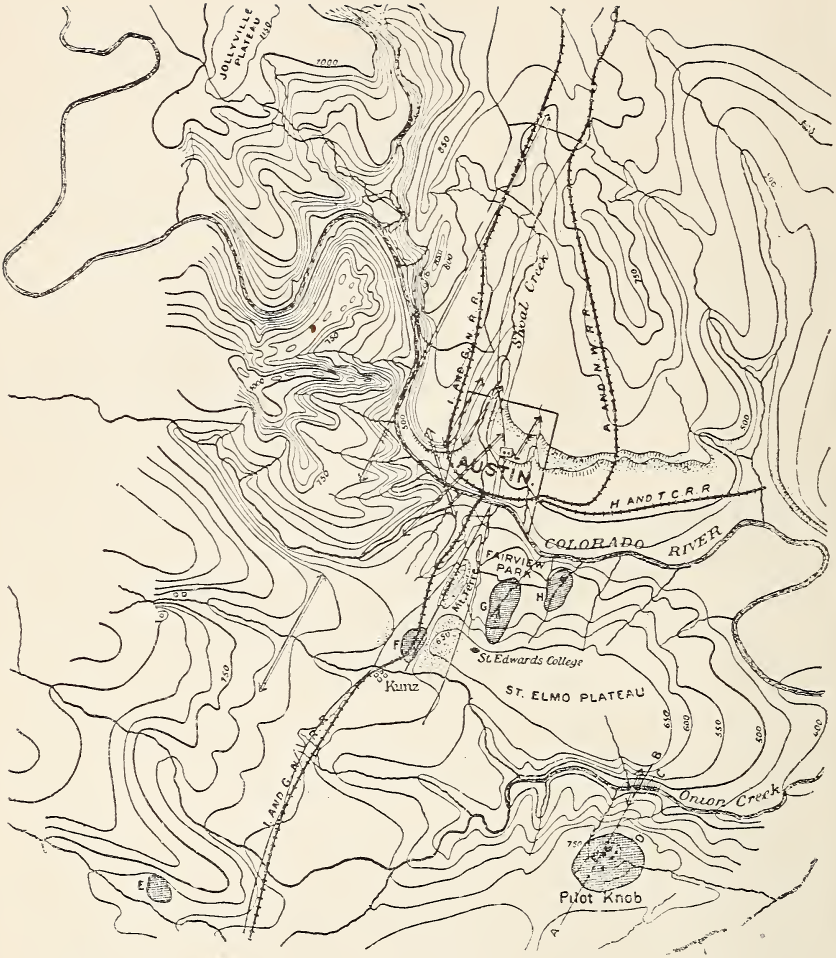


Fig. 8.

Map of Austin, Texas, and Vicinity, showing Outcrops of Igneous Rock (shaded areas) through the Water-bearing Strata of the Grand and Black Prairies and Breaking their Continuity.

and all other intervening points will no doubt meet with similar experiments.

This belt is at least 2,800 feet geologically above the face of Trinity sands, and 1,800 above the Lower Cross Timber sands north of the latitude of Hillsboro.

The only portion of the Grand and Black Prairie regions, where this water can not be made to flow, between the Colorado and the latitude of Denton, is on the tops and slopes of the high mesas ("mountains" in local parlance) which form the high divides of the stream valleys of the western half of the Grand Prairie, and are higher in altitude than the receiving area of the Upper Cross Timbers.

ARTESIAN FAILURES IN THE GRAND AND BLACK PRAIRIE REGIONS.

The proportion of failures in this region north of San Antonio have been remarkably small. Of the numerous wells drilled, only a few have been unsuccessful, and the latter, except in two instances, were not drilled down to the water-bearing sands. In but one instance has a well which penetrated to the Trinity sands failed to secure a rise of water, and this was at Taylor, where the second well drilled, in less than a mile from a most magnificent flow, was utterly dry, the Trinity sand especially so. I can offer no explanation of this, except that there was local imperviousness or perhaps certain conditions of faulting and slipping in the strata that cut off the sands from the water. At Thorndale, Marlin, and Terrel the wells were not drilled to the water. At Kerrville granite was struck at 700 feet. At Cable's Ranch, 12 miles west of San Antonio, 2,200 feet of the Comanche series were unsuccessfully penetrated.

Negative or non-flowing wells.—At Rome, Wise County, a well struck the water, but it failed to flow to the surface, because Rome is higher in altitude than the receiving area. The water rose sufficiently high to be pumped and is of great value. At the old well at Denison the water in a 1,200-foot well failed to flow for the same reason, that city having some 200 feet higher than the Trinity sands outcropping at Red River, at the great bluff below Preston. The value of nonflowing wells, however, should not be underestimated. Where the water rises to within pumping distance it is far more valuable than the surface water, on account of its freedom from organic matter. They can be obtained nearly everywhere in the region.

I have mentioned, p. —, a great fault or break in the strata from Marietta southwestward (followed by Red River from Preston to 7 miles east of Denison) towards Roxton and beyond, in Lamar County. By this great fracture the whole region of the Grand Prairie and water-bearing Trinity sands in Indian Territory has dropped below the altitude of the Red River tier of counties, so that there is no hydrostatic pressure to force it up south of the fault on the Texas side, as proven by the borings at Denison and Paris. On the Indian Territory side, however, it is different, and magnificent flows should be obtained from the Paluxy and Trinity sands in this region, under exactly the same conditions as previously explained of the Lower Cross Timber sands.

CONCLUSIONS AND SUMMARY OF THE ARTESIAN CONDITIONS OF THE BLACK AND GRAND PRAIRIE REGIONS.

It is now evident that this region of Texas is underlaid by several vast sheets of water-bearing strata occurring at various intervals apart. The lowest and most valuable of these are the Trinity or Upper Cross

Timber sands, which underlie every foot of the region and are the source of a probably inexhaustible supply. This is the lowest sheet of a group of water bearing sands at the base of the Lower Cretaceous or Comanche series, the highest of which, some 750 feet above it, is the Paluxy sands, which afford but a feeble flow and only extend under the region north of the Lampasas.

From 1,500 to 1,700 feet above the Trinity sands and 800 to 1,000 above the Paluxy beds is another group of water-bearing sheets, which outcrop in the Lower Cross Timbers, from which Dallas and Pottsboro receive their supplies. This sheet underlies only the Black Prairie region, and, while of great value, is not to be compared with the Trinity beds, which can always be struck by boring through it.

Having presented the geological character of the possible areas for securing water in the Black and Grand Prairie regions, I propose to show by the application of a simple rule how the approximate depth of the water sheets can be determined at any point. By drawing north and south lines through points of equal depth relative to mean sea level it may be granted that artesian flows can be obtained at any intervening point of that line, provided the surface altitudes are also similar. Thus a line drawn through Pidcock Ranch, Glen Rose, and Springtown will show that all along that line, at points of the same altitude, the Trinity water can be obtained at a less depth than 500 feet; A similar line through Georgetown, Belton, and Gatesville will cross all points where the 500 to 1,000 foot wells from the Trinity sands will flow; one through McGregor, Whitney, and Fort Worth will show the points where the 1,200-foot depth can be obtained ; one through Austin, Waco, Taylor, and Dallas, the 1,500 to 2,000 foot depth, and so on to the east. Furthermore, the depth of the artesian flows can be approximately prognosticated by a knowledge of the geological horizon outcropping at the surface. For instance, in the region where the Glen Rose beds outcrop the basal Trinity water sheet is not over 500 feet deep ; where the Comanche Peak division occupy the surface the Paluxy sands water is from 0 to 300 feet, and the basal Trinity or Jumbo flow from 500 to 1,000 feet; where the Fort Worth beds occupy the surface, the depth of the Jumbo flow is from 1,000 to 1,500 feet; in the region of the Lower Cross Timbers and Eagle Ford Prairies it is from 1,500 to 1,800, and along the line of the Dallas-Austin Chalk from 1,600 to 2,400, the depth increasing to the northward.

The depth of these wells depends upon their altitude and distance from the outcrop of the receiving area. This depth increases relative to mean sea level at the average rate of 30 feet per mile, and hence adjacent to the receiving area are shallow flows from 30 to 300 feet as at Glen Rose, Springtown, and Pidcock Ranch, while upon the eastern edge of the Black Prairie, as at Thorndale, Kaufman, Corsicana, and Terrell, these sands are over 3,000 feet in depth.

The pressure is inversely proportionate to the altitude of the wells, being greater where the point of overflow is lowest. It is owing to Waco's situation in the deep valley of the Brazos that her wells have such magnificent pressure, and it is owing to Dublin's very high altitude that her wells have a small pressure.

It has been a question with most well-drillers where to stop their drills. Many have the theory that the deeper the drill penetrates the strata the more will be the water obtained, while others, content to let well enough alone, have ceased drilling at the first flow of water obtained. Both of these hypotheses have to a certain extent been right, yet in their application they have often been wrong. The only sure rule

is to have a knowledge of the succession of the rock sheets and to govern the depth of the drill holes accordingly. The following rules, however, may be considered of value in determining the question:

1. If water is struck in the Lower Cross Timber sands the drill should continue at least 200 feet into the Fort Worth limestones, in order to obtain the benefit of all the flows of the sands. Below these the drill must go from 600 to 700 feet in order to reach the Paluxy sands, and from 600 to 700 feet below these to the main or Jumbo supply of the basal Trinity sands.

2. When the greenish-red clays of the Carboniferous system below the basal Trinity sands are reached, it is hopeless and useless to drill farther, as shown by the deep drilling at Fort Worth and at Cisco.

3. When the feeble mineral flows of the Paluxy and Upper Trinity are reached, the drill should by all means be continued from 200 to 300 feet deeper to the basal or Jumbo flow. Many of the earlier wells dug at Fort Worth, Morgan, Meridian, and Glen Rose should be deepened. (See profiles.)

THE ARTESIAN CONDITION OF THE BLACK AND GRAND PRAIRIES SOUTH OF THE COLORADO.

There are many reasons for separating the prairie regions south of the Colorado from those north of it. The chief of these is the great Balcones fault or fracture, which extends from north of Austin to beyond Del Rio, by which the continuity and arrangement of the stratification is greatly broken, the strata of the Grand Prairie or Edwards Plateau becoming more horizontal, while the Black Prairie has dropped down and is covered by the great La Fayette gravel sheet which extends along the Atlantic and Gulf seaboard and greatly changes the surface aspects of the region. Again, the great fault line is accompanied by a remarkable series of ancient volcanic necks of black basaltic rocks, which break through the water strata. For these I have proposed the name of Shumard Knobs.* (Fig. 8.)

These ancient volcanic rocks appear in upward of twenty places in the counties of Travis, Hays, Blanco, Comal, Kendall, Medina, Uvalde, Edwards, and Kenny.

Owing to their pressure it is impossible to predict the continuity of any area of flowing wells in the region, although the latter are numerous and abundant, while the great artesian springs here attain their greatest development.

The presence of these great masses of impervious igneous rock certainly render the certainty of artesian experimentation doubtful south of the Colorado and east of the International road in Travis County, where they cross from the Grand into the Black Prairie region. South of that point, along the International road to San Antonio, wells ought to be secured at most places within 40 or 50 miles of the escarpment. At San Antonio, as more fully treated in the chapter on the Rio Grande embayment, wells have been obtained and great abundance of flowing water, oil, gas, or all.

* See American Geologist, January, February, 1890. A typical one, Pilot Knob, more fully described in a recent paper. See "Pilot Knob," American Geologist, 1891.

WATER CONDITIONS OF THE EDWARDS PLATEAU.

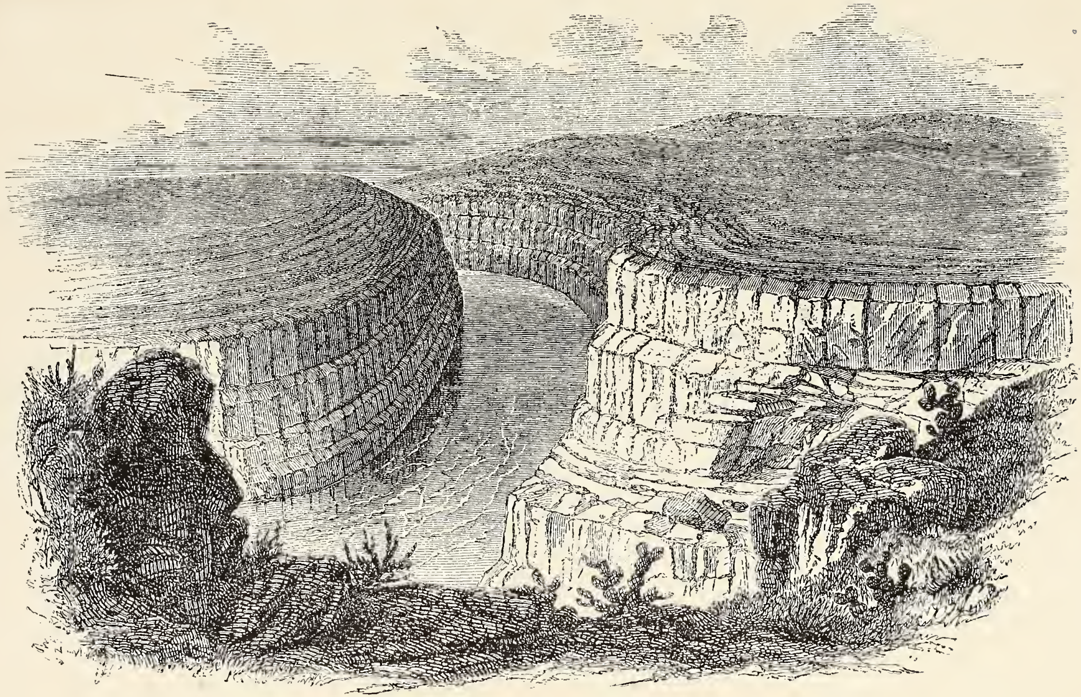
(See Plate II and Fig. 9.)

In the general description of the Kerrville plateau or southern division of the Grand Prairie, I have explained how it and its northward continuation—the Llano Estacado—forms a great elongated mesa or table-land, the northern half of which is covered by the great sheet of Tertiary strata of the Llano Estacado beds. The mass of the Edwards Plateau is mostly composed of spongy strata of the Glen Rose and Trinity beds, capped on the summits by the impervious Caprina limestone. By this arrangement, while the summits are dry, the whole mass of the interior and base of this immense mesa is charged with water like a sponge, which flows out at stream level on nearly every side and feeds all the streams south of the Colorado, as the Concho, San Saba, Llano, Pedernalis, Comal, Gaudalupe, Medina, Frio, Merces, and Devils rivers. These escarpment springs are often of great volume, like those of the Concho in Tom Green and adjacent counties, and all receive their supply from the earth water of the great mesa flowing out at the line of stream level, and never from the escarpment face or bluff. These characteristic springs can well be represented by placing a large sponge on a marble-top table and placing on top of the sponge a perforated sheet iron or grating. The grating will be similar to the jointed and fractured limestone cap of the Edwards Plateau, whose water percolates downward into the sponge and prevents it from evaporating. The sponge will be analogous to the Glen Rose and Trinity sands, capable of holding much water in saturation, even when dry around its edges. The marble represents either the impervious Red beds floor or the line of complete saturation in the Trinity beds themselves, which in either case will prevent the farther downward percolation of water, and, hence, by its own gravity it will flow or sipe out at the line of the lowest relative level, which is usually the stream beds. This is exactly the case of the springs of the great Edwards Plateau. The surface is dry and poorly adapted to agriculture, like the mountain tops (mesa) of the main Grand Prairie region, and has very little population. The deep canyons cut in to the spongy Glen Rose and Trinity beds form the sides of this mesa and usually have water and numerous springs, and in them is situated all the agricultural areas, but they do not constitute one per cent of the vast area for which the springs might be available.

The canyon springs in the eastern edge of the plateau, where there is more rainfall, are among the picturesque features of Texas, especially the valleys of the Guadalupe and Concho, and present unusually fine conditions for irrigation of the farming lands which border them.

The springs of this region are too numerous to give in detail, but the principal ones, beginning on the north, are the Big Springs of Howard County (in the transitional region between the Llano Estacado and the Edwards Plateau) which were admirably described by Mr. F. R. Roessler in the report frequently cited in this work. These springs flow from the Trinity sands, as since determined by specimens and sections furnished by Mr. Roessler.

Proceeding southward across the drainage divides (spurs of the main plateau) magnificent seepage springs of great volume are met in the valleys of the various branches of the Concho River, which have furnished water for irrigation in the Tom Green country for many years. These all break out from the Trinity sands and conglomerate. Continuing eastward, the next greatest springs are met in the Menard country,



Cañon of the Rio Grande, 105 miles above the Mouth of the Rio Pecos.
Showing structure of the Edwards Plateau. [Report of Major Emory, U. S. A., 1856.]

which flow as follows: McKavett, Block Springs, 300 cubic feet; Clear Springs, 1,200; Coglan Springs, 100; Elm Springs, 75. These springs originate the San Saba River; continuing around the eastern and southern border they increase in number until the Nueces is passed. In the Pecos Valley, Howard Springs, in Crockett County, are the last of the series of springs which drain the base of the Edwards Plateau.

On the surface of the Edwards Plateau water is reached only by deep wells from 3 to 500 feet in Val Verde County, which penetrate to the Trinity beds. These wells and their depths are given in the accompanying table. All experiments thus far have failed to reveal artesian conditions on this plateau from San Antonio to the Canadian, but this experimentation has been too limited to warrant any negative conclusions. In general these water conditions are of the same category as those discussed in the chapter on the Llano Estacado.

Non-flowing wells owned by the New York and Texas Land Company (Limited) in Kinney and Val Verde counties.

No. 1.—263 feet deep, 120 feet of water, 3 miles N. of Brackett.
No. 2.—257½ feet deep, 80 feet of water, about 5 miles N. 35° E. from Brackett.
No. 3.—274 feet deep, depth of water not given, 8 miles N. of Brackett.
No. 4.—299½ feet deep, 175 feet of water, about 10 miles N. 22° E. of Brackett.
No. 5.—378 feet deep, plenty of water, about 5½ miles N. 71° E. from Brackett.
No. 6.—289 feet deep, 130 feet of water, about 7 miles N. 49° E. from Brackett.
No. 7.—237 feet deep, about 9 miles N. 57° E. from Brackett.
No. 8.—150 feet deep, plenty of water, about 7 miles N. 68° E. from Brackett.

LINDHEIM PASTURE.

No. 1.—148 feet deep, plenty of water, about 10 miles N. 70° E. of Del Rio.
No. 2.—158 feet deep, about 7 miles N. 85° E. from Del Rio.

M'LYMAN PASTURE.

No. 3.—80 feet deep, 20 feet of water, about 16 miles N. 37° W. of Brackett.
No. 4.—65 feet deep, 25 feet of water, about 11 miles N. 22° W. of Brackett.

STANDARD PASTURE.

No. 1.—222 feet, 130 feet of water, about 13 miles N. 62° E. from Del Rio.
No. 2.—186 feet deep, 80 feet of water, about 16 miles N. 63° E. of Del Rio.

CROWL PASTURE.

There is one well on this pasture 85 feet deep, 30 feet of water, about 5 miles N. 60° E. of Del Rio.

UTILIZATION OF THE ARTESIAN WATERS OF THE BLACK AND GRAND PRAIRIE.

It is hardly necessary to dwell upon the need and value of water to the fertile region in which it has been obtained. A good water supply is the foundation of every civilization, and man's prosperity is usually proportionate to its abundance and purity.

In this special region the very qualities which make the soil rich have made the surface waters scarce, often impure, and more or less defiled by invisible germs of disease and malaria, the only afflictions with which this otherwise most healthy country is troubled. The city populations were especially restricted and inconvenienced by the lack of pure and abundant water supplies. Within the past few years all of this has been changed, and now we see the cities of Houston, Waco, Austin, San

Antonio, Fort Worth, Belton, Temple, Dallas, Denison, Denton, and Sherman (the latter a negative well) all drawing more or less abundant supply from underground sources, while hundreds of farms are annually supplied—giving increased value and new life to those places and an incalculable influence upon the material prosperity. Several of the large charitable and correctional institutions have also been supplied with this water, as the State insane asylums at Austin and San Antonio and the Reformatory at Gatesville.

In addition to the value of certain of these waters for their purity, certain others, as those from the Upper Glen Rose beds, at Georgetown, Waco, Pidcoke's ranche, Groome's well at Austin, and elsewhere, have superior medicinal virtues, resembling the celebrated Spas of Germany, which are found in somewhat similar rocks. These wells are of incalculable worth to the malarial region of the timbered coastal plain of east Texas, Arkansas, and Louisiana, and will undoubtedly be of great service to the people thereof, when they learn to appreciate them. The hygienic aspect of these waters, both the pure and the medicinal, will also prove of great value to the live-stock interests.

The industrial uses to which these waters are at present put are many. At Waco hundreds of sewing machines in clothing factories, electric motors, wood-working machinery, and other small industries are run by the pressure of wells, without wasting the water, by the use of small and powerful California wheels. When the high cost of fuel in Texas is considered, this use of artesian water becomes a most important factor.

The greatest use of this water at present is the fact that it brings to hitherto poorly watered farming and grazing lands an abundant supply of water for domestic and stock purposes, making small farms of 100 acres or less possible, where until recently subdivisions of large bodies of land or ranches were impossible, and, even in the rich black prairies around Waco, only large plantations could exist, each controlling a few surface wells or water holes from which the tenants or renters dragged for miles the dirty water in barrels on clumsy sleds, while in time of drought there have been failures of even the domestic water supply for large districts.

This condition has already changed, and Prather's well, for instance, on a farm south of Waco, alone furnishes more water than the entire surface supply of McLennan County, except the Brazos River, has hitherto afforded.

I drove during the great drought of 1877 from Decatur to Fort Worth, over a rich grass-clad region, without being able to secure a drop of water for myself or team the entire distance, while dozens of suffering teamsters were begging and trying to buy water from the owners of the few and all but exhausted surface wells along the way. With the knowledge now before us, every foot of that vast area of the Grand Prairie, being underlaid by water, could be cut into forty-acre tracts, upon each of which, if flowing water could not be obtained, magnificent negative wells rising nearly to the surface could be obtained, furnishing an abundance of waters unaffected by drought.

Irrigation of the Grand and Black Prairie region.—It is not the object of my report to discuss methods of irrigation, but to show the amount and availability of the water.

The rainfall of the northeastern portion of the Black Prairie region, (the portion where artesian wells are least possible) is abundant for all plantation crops, which seldom suffer there for water. The remainder of the region is more or less subject to drouth at intervals from five to

two years as we go eastward. All portions are subject to long, dry periods annually (usually in the autumn, after the corn and cotton has been laid by), during which gardens and fruits suffer greatly.

It is not my intention to convey the idea that the Black Prairie region is subject to drought; for crops of corn and cotton are often rich and abundant, but all admit that it has seasons of rain and drought, and that, if rich now, it could be made immensely richer by irrigation, and all the fruits and vegetables now imported from the irrigated lands of Utah and California could be produced at home.

The value of these wells for irrigation has been demonstrated by the modest farmers of the Paluxy valley, who by their own humble methods and without previous knowledge of the subject are now quadrupling the yield of cotton and grain. A farmer at Paluxy stated to me that his 10 acres of cotton, yielding nearly two bales of 500 pounds each to the acre, was far more profitable and easily worked than 100 acres which he had until recently cultivated in Alabama.

Irrigation from the artesian well is at present successfully practiced in the Paluxy region, and the largest and most prosperous city in Texas, San Antonio, is built upon and about an irrigation enterprise, which has most profitably and successfully utilized their underground waters for nearly 300 years, affording occupation for all the mission settlements in the past, supporting hundreds of gardens at present and destined to be of great value in the future.

Every drop of water from these springs and wells can be utilized for irrigation, and when the people of the region appreciate the fact that each gallon of water has a specific value in agriculture, as has a pound of coal in industrial enterprise, not one drop of this water will be allowed to escape unutilized, and the agricultural wealth will be enormously increased.

IV.

THE ARTESIAN SYSTEM OF THE RIO GRANDE EMBAYMENT.

I have explained on a previous page how the features of the Coastal plain changed south of the Colorado or Guadalupe and the great Austin-Del Rio escarpment into a more arid and generally different region. This includes the continuation of the Coastal prairie, the Washington prairie, the Timber belt, and of the Black prairie, and all the Rio Grande counties as far west as Val Verde, all Maverick, Encinal, Duvall, Nueces, Webb, Dimmitt, La Salle, Zavalla, Frio, Atascosa, Karnes, Goliad, Refugio, Live Oak, San Patricio, Wilson, and Aransas, and the southern or eastern portion of Uvalde, Medina, Bexar, and Guadalupe.

The ninety-seventh meridian, which is accepted as the western limit of reliable rainfall, intercepts the gulf at Aransas Pass, the eastern limit of this region, and if reports be true it certainly is in its lower part at least, one of the arid portions of Texas, a drought of over eighteen months' duration having been recently reported from Hidalgo within 100 miles of the coast. The rainfall however is much greater towards its interior margin, San Antonio, to Del Rio, where the drought has not extended. This region is in many respects the least studied geologically in Texas.

Its predominant and topographic feature is its generally low altitude; the contour or line of equal altitude (of 600 feet) which marks its western margin makes a great deflection westward along the escarpment of the Edwards Plateau, up the Rio Grande to Eagle Pass, thence back towards the coast on the Mexican side, and constitutes a great indentation, as if it had been a bay of the gulf which covered the region in comparatively recent geologic time. This is further proved by the extensive deposits of sand, gravel, and conglomerate that mark its interior margin, indicative of a late sea level, and remain in places over the whole area, but greatly divided by a still more restricted and recent event to be seen nearer the Rio Grande Valley.

I am inclined to believe this gravel sedimentation is the interior margin of the formation of the Fayette prairies.

The interior margin of this débris, visible from San Antonio to Uvalde, is only a thin inconspicuous sheet and bears no relation to the artesian problems.

The fundamental structure underlying these surface sheets in portions of the coastal incline is the system of rock sheets from the Eagle Ford shales (bordering the escarpment from San Antonio to Uvalde) on its interior margin to the coastal clays and prairies at the coast, with slight variations from the same beds seen in Texas north of the Guadalupe. This includes a great thickness of alternations of porous and imporous beds, many of which are artesian water reservoirs. The San Antonio water strata are the lowest geologically of these water-bearing beds. Succeeding the chalks and clays which overlie them is a great development of sands and sandstones in the glauconitic division of the Upper Cretaceous and Eocene, which here is entirely different (owing to the different conditions of original sedimentation in this Rio Grande embayment), from the Arkansas-New Jersey development. These, for which I have proposed the name of the Eagle Pass beds, outcrop from west of Eagle Pass to Webb County line along the Rio Grande, and occur all over the embayment as far south as the Santa Rosa Mountains in Coahuila. Succeeding these are various beds of the Eo-Lignitic Washington (Miocene) and coast prairies, in all of which wells have been found.

This region, as a whole, has not been prospected for water in many places, and in most of the counties, especially those east of the International and south of the San Antonio and Corpus Christi roads, wells have not been drilled.

In most of the instances where drillings were made the results were successful and water was obtained at less than 500 feet in instances, and in no case has a depth of 1,000 feet been attained.

From the results so far recorded, mostly in Mr. Roessler's paper, it may be safely said, that at least four well-defined water areas have been penetrated in this area, to wit, commencing with the lowest as follows:

1. The San Antonio or Black Prairie system.
2. The Eagle Pass beds.
3. The Carrisso sandstone of Owen's, in Dimmit and Uvalde counties (of Laramie or Eocene Age).
4. The Eo-Lignitic sands.
5. The Washington sands or Galveston-Houston coastal system.

The wells of San Antonio are being bored so rapidly and successfully that their number can not be given. They often flow oil and gas (from the Eagle Ford shales as at Waco), but water is reached at a depth of from 600 to 1,000 feet in a hard sandstone, which, although not proved, is apparently the Lower Cross Timber sands, which have no real outcrop, owing to the great fault to the west of the city.

A section of the earliest of these wells shows:

	Feet.
3. Soil, clay, and gravel of the Quaternary period	36
2. Blue clay soapstone and black (oleaginous) shale (Fishbeds or Eagle Ford shales)	610
1. A very hard sandstone with strong flow of water, the horizon of which has not been determined	5
Total	651

In one well, 4 miles south of the city, this sandstone was penetrated for 75 feet.

The field of these wells around San Antonio has been explored for 10 miles eastward with great success. Twelve miles west of the city, at Heliotes, where the Edward plateau sets in, the entirely different rocks of the Comanche series were passed through, and a drill penetrated 2,000 feet, at Mr. Cable's ranche, without getting a flow, indicating a different condition. The country similar to San Antonio east of the Balcones fault should be explored as far west as the Austin chalk and fish beds extend (to Uvalde at least), and wells will probably be found which will be of inestimable value to that region.

There is every reason to suppose that these wells can be procured at many places, most places, in fact, from San Antonio westward, between the Southern Pacific and the "mountains" (Balcones escarpment) as far west as the Nueces, where several small shallow wells have been already obtained in Uvalde County. At Spofford Junction a well was bored 1,800 feet without striking water or getting below the Denison clays, which would indicate that at and west of that place the favorable conditions had ceased for procuring water from the beds of the Cretaceous.

At Del Rio, still westward, where the greatest of artesian springs occurs, the surface strata, Washita and Denison beds, are 1,800 feet lower geologically than at Spofford, and a weak flow of very poor artesian water was obtained at less than 1,000 feet.

The Black Prairie has little width in this region, but is overlapped coastward by great deposits of sandy strata belonging to the Upper Cretaceous and later periods.

The source of the Eagle Pass wells is undoubtedly the sandstones of the Eagle Pass beds, the oil and gas being derived from the lignites which they contain. Inasmuch as these beds underlie all the great basin on both sides of the Rio Grande, from Eagle Pass to near Laredo, and the general inclination is towards the river, the region is worthy of further prospecting.

At Carrizo Springs, in Dimmit County, and westward, there is a great sandstone deposit beneath the surface which has been named the Carrizo sands by Mr. J. Owen, the excellent geologist of Eagle Pass. (See preliminary report of the Texas State Survey.)

This sandstone has a wide outcrop in western Dimmit, southern Uvalde, and northern Nueces counties, surmounting the Eagle Pass beds. Several fine wells have been procured from the Carrizo sands, which have been reported by Mr. Roessler.

The extent and capacity of the Carrizo sands is yet to be determined, and there is little doubt but they will prove a most profitable and extensive artesian area, in the counties of Webb and Dimmit, and the region should be most thoroughly prospected.

The Atascosa wells, or Eo-Lignitic sands. At Pleasanton (altitude, 300), in Atascosa County, a well was secured at 108 feet. Not having

been able to visit this point, I can only base my judgment upon the evidence of others, which leads me to believe that these waters come from the sands of the Eo-Lignitic * or Camden beds which underlie the great timbered region of Texas and eastern Arkansas. If these are the same sands from which Marshall and other cities of Texas secure artesian water, it should supply a means of great development for Atascosa and adjacent counties.

The wells of the coastal region are derived from the Washington and Fayette sands.

The same beds which underlie Houston and Galveston extend along the coast southwestward and supply artesian flows at Yorktown, Velasco, Gonzales, Cuero, and San Patricio, at shallow depths varying from 40 feet at Yorktown to 966 near Patricio. There is little doubt but that these wells can be obtained along the whole coastal region for 50 miles inland.

I have now discussed the great artesian conditions of the coastward incline of Texas, and can only add that in this whole region, with the exceptions noted, wells can be obtained at moderate depths.

The slight coastward slope of the whole region and the corresponding inclination of its underlying beds indicate a good supply from one or more of the underlying sandstones anywhere that a well will be drilled deep enough. While the flow may be small, even any amount will be a great boon to the region.

V.

WATER CONDITIONS OF THE CARBONIFEROUS AND OLDER PALEOZOIC REGION OF CENTRAL TEXAS.

Good wells (nonflowing) are abundant throughout most of this region, and several small artesian wells of poor quality and flow have been reported. Concerning this region Mr. Roessler has said:

> Between the ninety-ninth and one hundred and first meridians the borings have been failures throughout. In most cases, as at Cisco, Eastland, Baird, Colorado, and Big Springs, no flow was secured, leaving the few small shallow wells at Wayland, Stephens County, out of the calculation on account of their small flow. Where a flow has been secured, it was either mineral or impregnated with salt, coal gas, etc., as at Trickham, Coleman County; Gordon, Palo Pinto County; San Antonio, Eden, Concho County, and other places. The pressure necessary for artesian wells is present in all the wells mentioned.

The structure of the region is unfavorable for any large flow of water, and I do not advise further experiments. In Burnet County one or two small flows have been secured out of hundreds of borings made with the diamond drill by mineral prospectors.

* For a full description of the lithology of these sands, see report of Arkansas State Geological Survey, Vol. 2, 1888.

VI.

WATER CONDITIONS IN THE RED BEDS REGION.

[Western Indian Territory, the Canadian and Pecos valleys of New Mexico, and the Abilene, Concho, and Wichita countries of Texas.]

This region is one of the most striking and important of the geographic features of the Southwest. Its name is derived from the fact that the surface of the whole country underlaid by it is of conspicuous red colors, glaring vermilion or deep-brown chocolate sometimes prevailing, varied only here and there by a bed of snow-white gypsum. To one accustomed to the green-clad landscape of the east or its somber-colored formations, the vast landscapes and brilliant colors of the Red Beds is striking, especially if seen in some bold cliff for scores of miles. A landscape in color that of red brick dust is the only familiar comparison.

These beds occupy a vast extent of country in Oklahoma, Texas, and New Mexico, aggregating 100,000 square miles, as seen upon the map, occupying all the nonmountainous region, except where covered by the Llano Estacado formation, from southern Kansas to the trans-Pecos Mountains, and westward around the southern termination of the Rockies, through New Mexico, Utah, and Oregon, to the Sierras. They have not been recorded far south of the Southern Pacific Road, nor do they anywhere appear in Mexico north of Catorce, the Cretaceous still covering that area. The valleys of the Canadian and the Pecos reveal their presence beneath the Llano Estacado, and the Grand Cañon of the Colorado shows them in Arizona and Utah. Occasionally they appear in the flanks of the Rocky Mountains. Their characteristic and most perfect exposures are in the country between the ninety-ninth and one hundredth meridians south of the Arkansas and north of the Conchos, embracing portions of Texas, Indian Territory, Oklahoma, No Man's Land, and nearly all of Oklahoma, where they occupy beautiful prairies, including those of the celebrated Wichita, Concho, and Abilene countries, which embrace fine agricultural lands of Texas and the Oklahoma country. They also include much of the Pecos Valley, especially east of Eddy, between the river and the plains, and from Roswell northward to near the crossings of the river and the Santa Fe Railway.

Along the eastern escarpment of the Llano Estacado and up the cañons of the Brazos, Colorado, and Red rivers that incise it, and up the valley of the Canadian, there are beautiful bluffs of these vermilion beds, with an occasional butte or mesa.

These beds constitute the foundation of the northern and eastern edge of the Llano Estacado north of the Colorado.

The principal area of the Red Beds is that of western Indian Territory and northwestern Texas, between the Llano Estacado on the west and the Coal Measures on the east. This stretches from the thirty-eighth to the thirty-second parallel, a distance of 350 miles north and south and from the ninety-eighth to the one hundredth degrees of longitude, or averages 150 miles in width, a total of 52,500 square miles—an unbroken prairie, except small areas occupied by the Witchita Mountains and a few remnant buttes of the Grand Prairie and Llano Estacado formations which have been preserved to remind us of the vast erosion the region has undergone.

The next area in size is in north central New Mexico, on either side of the Canadian and Pecos, after those streams have emerged from the mountains and adjacent plateaus. This valley is an enormous trough

furrowed out of the Raton and Llano Estacado plateaus by erosion. Its northern boundary is the superb Corazon escarpment which runs eastward from Pecos, crossing to the Texas line. This escarpment, as shown upon the topographic maps of the United States Geological Survey, is over 1,200 feet in height above the Canadian River. It extends irregularly northeastward for 100 miles until overlapped by the plains surrounding a magnificent valley of the Red Beds, in the lowest portions of which the drainage of the Canadian and Pecos are at an altitude of 4,000 feet, or over 2,000 below its summit.

This valley plain is irregular in outline, as shown on maps, but of great area. In it the drainages of the Pecos and Canadian separate on their long and different journeys to the sea around the northwest escarpment of the Llando Estacado, which looms up in the distance like a mystic wall. Language can not describe the magnificence of the scenery; everywhere upon it is seen the grand and deep erosion by which the overlapping formations have been stripped from the horizontal Red Beds, and, as if to make the fact more impressive, nature has left standing in the valley numerous remnants of the plain in the shape of great circular buttes and mesas as El Corazon, the Gavilian Mesa Rico, Mesa Redondo, the big and little Huerfano, Mesa Tucumcarri, and others, every stratum of their red and white beds visible for miles and showing the lack of artesian conditions. These superb buttes of the Canadian valley are among the most interesting features of our country, and as they have been the subject of much controversy, I present a description of one of them by Capt. Jas. B. Simpson, U. S. A., written some forty years ago.*

Soon after taking up the line of march a small, faint, cloud-like appearance of small but growing extent exhibited itself, bearing magnetically nearly west. A few miles further on this appearance gave away to a well-defined truncated one. Proceeding still further on, and in proportion as we progressed, a dome-like appearance gradually unfolded itself, till at length, when we had almost reached our present camp, an assemblage appeared which did not fail to strike many of us as being an excellent representation of the dome of the Capitol at Washington. This object, which we have been gazing at nearly all day with the greatest interest, we take to be a Cerro de Tucumcarri. Passing over a poor soil we reached Cerro de Tucumcarri. After a laborious ascent, of which some fifty feet were nearly vertical, we reached its summit. On every side was an unobstructed view. To the west and south lay a confused mass of irregular hills, with here and there a well-defined and conical one to characterize the scene. Far behind to the west lay a range of mountains or hills and more conspicuous than the rest of the high peak. To the south, some 8 miles distant, I could see with my reconnoitering glass the serrated tents of our command, reposing on a timbered affluent of the Canadian. To the southeast and east lay the famous 'Llano Estacado' of the Mexicans. To the northeast and north lay a limitless, unbroken, and undulating prairie, no signs of the Canadian being apparent. Pacing the top of the mound, I found it to be 230 yards, by 370 in area; and, by a measurement of the slope of the hill and roughly reducing it to an angle of 45 degrees, I made its height over 700 feet (900 feet above the Canadian). The circumference of its base to our surprise I found to be nearly 6 miles, it having taken a horse two hours less eight minutes to walk around it. (P. 14.)

Following up Tucumcarri Creek, a fine view made up of sugar-loafed hills and tableau mounds, and opening vistas, presents itself to your front. The regular stratification of these hills, their pearly white and red color in horizontal zones, and the whole surface besprinkled as they are, with stunted cedar of a dark-green color, will not be failed to be noticed by the traveler as giving them a very beautiful and unique character. The formation of these hills, which are from 100 to 300 and 400 feet high, is at the base a red argillaceous rock, the Red Beds, easily frangible; next proceeding upward, a zone of sandstone rock (the Trinity Sands), very friable and of a greenish-white color; last and uppermost, a sandstone rock (the Dakota Sands), of a brownish hue and rather coarse character. Large fragments of these last-mentioned rocks lie scattered on the tops of the hills."

* Thirty-first Congress, first session, House of Representatives, Ex. Doc. No. 44, Report of Exploration and survey of route from Fort Smith, Ark., to Santa Fe, N. Mex., made in 1849, by Lieut. James H. Simpson, Corp of Topographical Engineers; also a report on the same subject from Capt. R, B, Marcy, Fifth Infantry.

The writer has twice visited the Mesa Tucumcarri and found it a most interesting geological remnant of the former area of the Llano Estacado. The table or summit described by Capt. Simpson is covered with the typical Llano Estacado formation, identical in composition and formerly continuous with the sheet which covers the Llano proper, some 20 miles distant. Below this is a vertical escarpment of 50 feet or more of typical Dakota sandstone resting upon loose sands and clays, forming a slope identical in aspect and fossil remains with the Denison beds of the Washita Division, which have been eroded away from the 400 miles intervening between it and the main body of those beds at Denison, Tex. Beneath this is a large deposit of the typical Trinity sands country, of white pack sands, thin clay seams, and flagstones, while the base is composed of the typical vermilion sandy clays of the Red Beds.

This valley has several small creeks at intervals of 15 to 30 miles apart, such as the Concho, La Cinto, Truxillo, Plaza Largo, and one or two others, the water of which is all the escarpment drainage of the Llano and could be used for irrigation of about 1 acre in 1,000 of the beautiful land, as is now used at Dutch Henry's Ranch, the only Caucasian settlement between Las Vegas and Bell Ranche, 100 miles east, where a steam engine is used to irrigate about 20 acres. The scarcity of fuel, however, would not allow this mode of irrigation to be extensively used.

Around the edges of the escarpment of these valleys there are occasional springs many miles apart which usually have their origin at the contact of the Red Beds and the overlying sands of the Dakota or Llano Estacado, from which the water is derived, and which will be discussed in these chapters relating to those formations.

In the Red Beds proper there are few wells, the only one of note being that at the cattle ranch at the northeast base of Tucumcarri Mesa, which supplies an abundance of water, which is pumped for cattle; this leads us to infer that others could be obtained.

The Red Beds also extend down the valley of the Pecos from its divergence from the Canadian around the western border of the Llano Estacado. This prolongation continues to the Texas line and occupies nearly 5,000 square miles of area. From Eddy to 60 miles south of Pecos they are overlapped by later formations, but appear again in the vicinity of the Castle Mountains. There are other isolated patches in eastern and central Mexico of considerable area, of which details must be omitted.

The Red Beds are composed of finely comminuted material, mostly red clay and sand, usually thoroughly mixed together, accompanied sometimes by beds of coarse, loosely cemented, greenish and chocolate colored sandstone, which weathers into circular turban-shaped masses. Occasionally, as at Guthrie, Okla., and Tascosa, Tex., there is a species of conglomerate, the pebble always being composed of the sands and clays of its own beds. While, no doubt, a continuous and unbroken formation from the bottom to the top, there are other variations in structure which are here noted.

In their lower portion there are darker-colored chocolates, and copperas green tints occur frequently, and a greater amount of rounded sand of varying coarseness. The rocks of this division are well displayed in the southeastern half of Oklahoma, at Henrietta, Colorado City, Tascosa, and other points in Texas, and in the valley of the Canadian from the mouth of Cañon del Agua, New Mexico, to east of the Texas line. Occasional fragments of fossil wood and remains of plants, reptiles, mollusks, etc., have been reported from localities which I believe to be in these

beds, and ascribed to the Permian age. This lower division of the Red Beds is also characterized by excessive cross-bedding and lack of persistent planes of stratification.

The beds become finer, more argillaceous and gypsyferous in their middle division, as can be seen in the fine brick-dust clays of the Pecos and Canadian valleys (notably the base of Sierra Tucumcarri), in the lower third of Cañon Blanco, in the eastern edge of the Llano Estacado, and in the vicinity of Sweetwater County, and Vernon, Wildbarger County, Tex.

The escarpment of the Llano Estacado in Texas and New Mexico, affords superb displays of these brilliantly-colored strata, often alternating with bands of pure white, saccharoidal gypsum.

The beds of gypsum occur over a great area and its quantity is inexhaustible (Fig. 10). The strata are from a few inches to 20 feet in thickness, usually of a pure white color, presenting a strong contrast with the vermilion layers with which it is embedded. It is present in Kansas, New Mexico, Oklahoma, and Texas in great abundance, and is the most important economic feature in the whole Red Beds region, in that its presence is the basis of the fertility of the Red Beds and it is readily soluble in water and usually accompanied by it. The water is often so strongly impregnated with it that the term "gyp water" is a common expression throughout the region. Although until recently unappreciated it is rapidly becoming an important economic feature, and is being manufactured into plaster Paris, an adamant wall plaster, in great quantities.

Gypsum also occurs in bright crystals resembling mica, for which it is commonly mistaken. In eastern Mexico the gypsum is often soft like pulverent flour and is known as jeso (yaso). This jeso is often mistaken for the injurious "alkali," when in fact it is a most important element in the fertility of a soil. Miles and miles of jeso can be seen in the Pecos Valley where it is blown about by the winds.

In the Tularosa Valley, at the head of the Franklin-Hueco basin, the gypsum is granular and is known as the white sands. These sands extend for many square miles and resemble siliceous sand. They contain a great amount of water and it is only necessary to dig a few feet to obtain wells throughout their extent.

The term Red Beds is geologically used to denote the vast series of red-colored deposits below the well defined Trinity sands and above the undoubted Permo-Carboniferous. Their age (which is utterly immaterial to the question of artesian water) certainly ranges from Permian at their base, as shown by the investigations of Cope, Boll, and White, in Wichita counties of Texas, to Triassic, as shown by Newberry and Marcou, in Texas and New Mexico, and probably Jurassic—continuing to the base of the Comanche series, as seen in the Cheyenne sandstones of Kansas and at the base of Tucumcarri, N. Mex.

Whatever their age, they have the same unmistakable characteristics of color and unconsolidation and are probably a single unbroken formation, representing the sediments of an ancient inland sea, which extended from the ninety eighth meridian westward to the Sierras and from the northern United States nearly to Mexico.

The beds of the flowing rivers arising in the escarpment of plains are in the Red Beds formation, to-wit: The Cimarron from near the one hundredth meridian to east of Guthrie. The Canadian from Camp Supply to the Santa Fe Railroad. The Red River from its head in Cañon Blanco to Montague County, Texas. The Pease and Wichita from their head to mouth. The Brazos, from its head to Young County.

The Colorado and tributaries from source to near Ballinger, Runnels County; the Pecos from the mountains to Roswell, N. Mex., and from below Pecos city to beyond Castle Buttes.

Although these rivers flow through and drain the Red Beds in time of floods, not one of them has its permanent or spring water supply from them, all receiving their water either from the underground drainage of the Llano Estacado or the mountains, but in flood times these streams are all characterized by their phenomenal vermilion-colored freshets, ordinarily known as "red rises," which flow down in great volume after the sudden and excessive rainfalls, which come in June, July, and August, in the Red Beds region.

If the stream drains the Red Beds only, as the Pease and Wichita, all of its rises are of this vermilion hue, owing to the excessive Red Bed sediment which they contain. If it flows through a diversity of geologic formations and finds its way into the humid region, like the Brazos, Red, and Colorado, then its flood will vary in color with the prevalent color of the rock of the region upon which the rain has fallen. Thus, at Austin, on the Colorado, where these floods come often in times of local drought, the extent of the region affected by rainfall can always be told by the white and red rises—the former coming from the limestone country, and the latter from the Concho-Colorado red lands country. If there has been rain in both, the white flood precedes the red.

The lower beds from their coarser structure and excessive cross-bedding present few conditions for the storage of water, and as a rule springs are few and rare. In fact, I do not know a single spring coming from these beds of sufficient size to be valuable for extensive irrigation, though often they are large enough to supply domestic purposes

Surface wells are obtained of large capacity, but as a rule are rather deep and scant, except along the less arid eastern border of this outcrop.

I have as yet failed to observe a single flowing artesian well in the Red Bed area, and doubt if one can be obtained, although one has been reported near Seymour, Tex., the water being of small flow and highly impregnated. The pervious basal layers are too irregular and unreliable to convey water to a great distance, and the upper or Triassic division too impervious. In Texas and New Mexico the conditions of dip and induration are inevitably against the topographic slope, and hence unfavorable to artesian conditions, as seen in the sections and figures.

The springs in the valley of the Canadian at Tascosa, which rise apparently from the Red Beds, I am inclined to believe have their origin in the neighboring Llano Estacado beds, which cap the adjacent mesa edge.

In Indian Territory and Oklahoma the inclination of the strata is different and of a nature to warrant the conclusion that experiment in those regions is justifiable.

The largest and most favorable non-flowing well observed in the Red Beds was that of Col. E. C. Eddy, at his headquarter's ranch, 25 miles east of Eddy on the Pecos, New Mexico. Here in the center of a large basin, which is apparently a lake in time of rainfall, a well has been dug to a short depth, and 3,000 cattle are daily watered by aid of a pump, which is of the chain-bucket type, and operated by horse power. Numerous other wells in the area of the Red Beds lying in the Pecos, between the escarpment of the Llano Estacado and the Guadalupe district, have led the writer to infer that non-flowing water will be found quite abundantly in all of these lower areas.

Experimental wells have been bored in the Red Beds at Colorado City and at Abilene, the latter having descended 1,000 feet at last reports, with no success. At the former place salt was struck at a depth of 760 feet. All deep wells in the Red Beds strike salt.

VII.

WATER CONDITIONS OF THE LLANO ESTACADO.

For that portion of the great plain proper lying south of the Canadian River and east of the Pecos the term Llano Estacado was appropriately applied by the early Spanish explorers. In surface features the northwestern half of this plain is similar to the plains of Colorado, Kansas, and northward, but differs from them in that, instead of extending to the Rocky Mountains on the west or imperceptibly grading into the level of the eastern areas, it is surrounded on every side, except a few miles at its southeast corner, by a more or less precipitate escarpment of erosion resembling palisades, which completely insulate it from connection with other regions, except the Edwards Plateau, which is its southeastern continuation and genetically a portion of it.

The vast surface of the Llano Estacado, at least 50,000 square miles, is practically smooth with the exception of an occasional depression, so much so as to resemble the level of the ocean at dead calm and unbroken by trees or bushes or deep drained channels, and carpeted with a rich growth of gramma grass.

Within the past few years the new railroads of Texas and New Mexico have made accessible to the geologist this largest of all Texas plains, and perhaps areally the greatest continuous and least studied plateau of our country. (See Pl. II.) Geographically the "Staked Plains"* of Texas and New Mexico include the quadrangular region south of the Canadian, east of the Pecos, and west of the one hundred and first meridian. The small amount of surface water, which is not imbibed by the soil, is found in a few widely-distributed ponds. Its eastern and northern edges are incised by deep and vertical cañons of streams which are cutting by backward or headwater erosion. Two streams flow around the plains. These are the Canadian and Pecos, both of which have cut nearly 1,000 feet below its level and neither receives any of its surface drainage. The rainfall, principally from June to September, is estimated from 20 to 25 inches.

* The name Staked Plains should be dropped from geographic nomenclature as the descriptive name for the great mesa to which it is applied. One popular apology for the use of this term is that early travelers set up stakes to mark their roads over these—then considered—waterless wastes. Another is that the term alludes to the staff-like stems of the yucca plant, which resemble stakes projecting above the ground. Neither of these hypotheses, however, will stand the test of application, for the traveler could not possibly have secured on the absolutely treeless plains timber wherewith to make his stakes, and the yucca does not grow upon them. Upon the other hand, a glance at the Spanish dictionary will show that it will be impossible to translate the word "estacado" to mean a stake, but upon the contrary it means exactly the opposite, a palisade or wall, which is a most appropriate descriptive term for the Llano Estacado, inasmuch as it alludes to the sharp declivity or face of the escarpment which in many places marks the edge of these plains. In view of these facts it is as erroneous to use the term Staked Plains for the Llano Estacado as to write the name L'Eau Frais, "Low Freight," as is done upon maps of Arkansas.

OUTLINE
OF THE
LLANO ESTACADO
AND ITS
MARGINAL DRAINAGE.
WITH
Cross Sections Showing
Water-Bearing Strata.
Volcanic Necks along the Balcones Fault and Spring Line.
Las Vegas
Rio Canadian
Tascosa
Amarillo
Red R.
Rio Brazos
Roswell
Guadalupe
Mts.
Eddy
Big Springs
Rio Pecos
Pecos
Rio Colorado
South Limit of Llano Beds
Edwards Plateau
Austin
Line
Fault
San Antonio
The Balcones
Del Rio
Rio Grande
B
A
D
C
F
E

SEx 41 52 1

The surface of the plain is everywhere composed of the transported sedimentary soil described as the Staked Plain formation, which is from 10 to 30 feet deep. From its structure and composition, it is evident that it is either a deposit laid down in late miocene time. The formation and its resultant soil differs from all others in Texas, and notwithstanding the deficient rainfall the plains are covered with short, nutritious gramma grass. Although apparently level, this great plain inclines rapidly seaward, at the rate of 20 feet per mile, its western margin having an altitude of 5,000 feet, and its eastern only 2,500.

Owing to the excessive porosity of the soil, the surface is void of deep-cut drainage channels, such as creeks, rivers, and cañons, although the Pecos and Canadian have cut completely across and through it, and many stream like the Red, Brazos, and the Colorado, by headwater erosion, are rapidly incasing its eastern border, and will eventually destroy it. (See Pl. II).

The escarpment of the Llano Estacado is one of the most remarkable topographic features of our continent, presenting from almost every view the appearance of a precipitous wall, often visible from 50 miles distant, escalloped or serrated by rain washes, like the bluffs of the Mauvaise Terre or bad lands of the Northwest. The western portion of this escarpment, extending from the Canadian, in New Mexico, to the Rio Grande, Texas, in a southeasterly direction subparallel to the Pecos River, is apparently unbroken by an interceding drainage. It extends east of Sumner, Roswell, and Eddy, and is the eastern limit of the drainage basin of the Pecos River, which stream, now 900 feet below its general level, has no doubt destroyed the former western extent of the Llano Estacado and its contact with the mountains, from which it is now everywhere from 50 to 100 miles distant.

The northern escarpment forms the southern bluff of the valley of the Canadian River. This escarpment is the most precipitous of all and is exactly similar in general features to the opposing bluffs of the Corazon, mentioned in the chapter on the Red Beds.

The southern continuation of the Llano Estacado is the Edwards Plateau (previously described), which is a part of the plain and a result of the same geologic causes, although different in underlying structure.

As was remarked by Capt. Mayne Reid in one of his early romances of the prairies, the Llano Estacado is simply a vast quadrangular mesa, which is elevated above all surrounding regions. Its slope and precipitate border can be likened to a book resting upon a flat table.

The geological structure of the Llano Estacado is as simple and uniform as its topography, consisting of a surface or capsheet of unconsolidated porous sediments, composed mostly of waterworn sands, pebble gravel, and silt, occurring in horizontal layers and averaging 200 feet in thickness throughout its extent, as ascertained by numerous well borings and measurements of the escarpments. The greatest thickness of the formation is towards the eastern margin of the plain, gradually thinning westward.

The peculiar heterogeneous character of the unconsolidated formation has been well described by Prof. Robert Hay, as grits, mortar beds, and marls. Certain layers are composed of hard siliceous gravel which are recognizable as the débris of well-known Rocky Mountain formations. Others consist of coarse waterworn quartz sand, loosely cemented by a lime matrix, so that it is literally coarse mortar beds. The marl is usually pinkish or light chocolate brown, and when watered forms a rich agricultural soil. Another typical aspect is known to the

Mexicans as the "tierra blanca," or white earth. This is found as strata of a white calcareous chalky earth possessing strong hydraulic or setting powers, and usually the protecting or cap layers of the escarpment. The tierra blanca is well shown, north of Tascosa, in the bluffs of the Canadian; in the bluffs of the Palo Douro Cañon; in the railway cuts of the Texas Pacific, west of Sweetwater, Nolan County; and in the western escarpment along the Pecos Valley.

This porous unconsolidated structure of the Llano, as will be shown later, has important bearing upon its water conditions.

These sediments may have been the deposit of a vast lake which occupied the region of the great plains in late Tertiary time, but I am inclined to believe them the marginal deposits of the Gulf of Mexico. although different in physical character from other formations, discussed in this report, of marine origin and different conditions of oceanic sedimentation.

This formation has been described minutely by Newberry, Hay, and Shumard. The descriptions by Prof. Newberry of the plains of western Kansas and No-Man's Land, although he was not aware of the similar structure of the Llano, are so applicable to the latter region, which is the same formation, that it is here given in his language. He says: *

> The detail of structure of the Tertiary basin of the Arkansas will be, perhaps, most readily understood by a few extracts from my notes, made at various points along our journey, where the Tertiary strata are exposed. "After leaving Pawnee Fork the road passes over the level bottom lands for several miles, * * * when it rises out and crosses the table-land, which separates the valleys of Pawnee Fork and the Upper Arkansas. This table land is underlain by a white tufaceous limestone, exposed in the bed of the Coon Creek, and still better at the point where the dry road comes down again to the Arkansas. It is also thrown out in many different places from the burrows of the prairie dogs. In lithological characters this rock is precisely like a portion of the strata of the bad lands of Nebraska, contains no fossils, but a few pebbles of crystalline rock. At the Caches, 16 miles below the crossing of the Arkansas, the same stratum is seen overlain by some 30 feet of coarse, soft, light-brown conglomerate, much cross stratified. The cement is coarse siliceous sand; the pebbles, from the size of an egg downward, of granite traps, quartz, trachyte, jasper, quartzite, charb, etc., with a few of Carboniferous limestone.
>
> "At the crossing of the Arkansas the following section is exposed: 1. Spongy tufaceous limestone like that on dry road. 2. Coarse soft conglomerate, same as at Caches, 35 feet. 3. Tufaceous limestone, like No. 1, to base. The sand hills which border the Arkansas on the south side seem to have been derived from the decompositions of the Tertiary conglomerate.
>
> "The same stratum forms the banks of the Cimarron, and has apparently given character to its sandy and sterile valley. The 'Jornado,' the divide between the Arkansas and the Cimarron. is another portion of the high prairie, precisely alike in typical and geological structure that crossed by the 'dry road.'"
>
> At Eighteen Mile Ridge, on the Cimarron, the coarse conglomerate and chalky tufas are exposed, as at many points below. The conglomerate is composed of a coarse sandy cement with pebbles from the size of shot to 8 inches in diameter. The larger ones are compact, fine grained, reddish yellow sandstone, doubtless of lower Cretaceous age, and such as comes to the surface further westward. Others are composed of granite, amygdaloid, clay slate quartz, jasper, etc. The greater size of the pebbles in the conglomerate indicates that, in going westward, we are approaching the source from which they were derived. The conglomerate would seem to be a drift from the Rocky Mountains, where and where only, as far as I am aware, such materials occur in place.

Along the cañons of the head of Red River, at the northeast corner of the Llano, the deep incisions have been made, revealing escarpments excelled in beauty by only those of the Grand Cañon of the Colorado, which they much resemble in color and stratigraphy. Several

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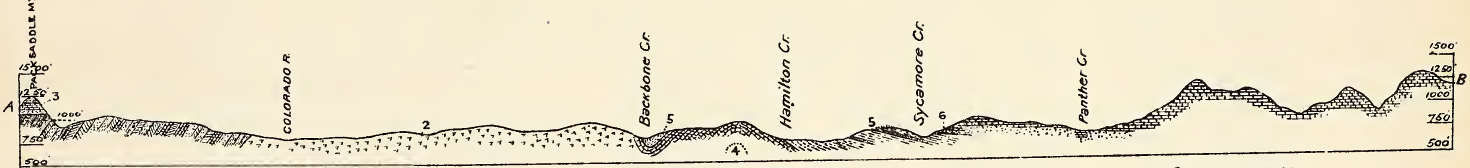
* Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Colorado of the West, in 1859, under command of Capt. J. N. Macomb, Corps of Topographical Engineers, with geological report by Prof. J. S. Newberry, 1878, geologist of expedition, pp. 24 and 25.



SECTION From MARBLE FALLS
TO TRAVIS PEAK SHOWING BASAL WATER BEDS OF COMANCHE SERIES IN CONTACT
WITH THE IMPERVIOUS PALEOZOIC FLOOR AT SYCAMORE CREEK

1 LLANO SCHISTS
2 CAPITOL GRANITE
3 POTSDAM SANDSTONE
4 SILURIAN LIMESTONE
5 CARBONIFEROUS
6 TRINITY SANDS
7 ALTERNATING BEDS

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sections have been published of these and beautiful illustrations given in Capt. Marcy's Report on the Exploration of Red River of Louisiana, and by Dr. G. G. Shumard, and later by Rev. W. F. Cummins.

In general these sections show the following succession:

			Feet.
1.	The Llano Estacado beds prevalent color: Light chalky, showing occasional faint tints of yellow and pink.	Loose surface soil, sandy red	8 to 20
		White calcareous "pan" or tierra blanco	2
		Sands usually slightly compact	2 to 10
		White pan, often siliceous and honeycombed	2 to 5
		Impure calcareous sands and clay	30 to 40
		Tierra blanco	2 to 10
		Loose rounded sands, mortar beds	20
		Greenish white clays	30
2.	Upper Red Beds. Red vermilion clays forming lower cliffs of cañon, and showing an exposure of		150 to 200

This surface formation of the Llano extends southward of the Texas Pacific onto the Edwards Plateau an indefinite distance. It reaches the Rio Grande, in Val Verde County, north of Del Rio; and I am inclined to believe that it once covered the whole of the Edwards Plateau and has since been eroded. There are features in the coastward regions of Texas, in the Rio Grande embayment, closely related, which I have described as the Washington prairies.

The floor of the Llano Estacado, or that portion underlying the above-described cap formation and outcropping as the basal portions of its escarpment, is of entirely different material, and since it is of great importance to the water question it must be described.

Its relation to the Llano formation can be conceived, however, by considering the present diversity of formations outcropping, *i. e.*, constituting the earth's surface, sands, clays, granites, etc., and imagining a great subsidence which would reduce these to a common base level and spread over the diverse rocks a sheet of sediment like that of the Llano. It was upon such a surface as the present that the cap sheet of Llano sediments was laid down, which, although concealed as by a veil, let us examine for a moment in order to understand its relation to water. (See profiles on Pl. II.)

Toward the north this floor was eroded down to the Trinity sands previous to the deposition of the Llano beds, and even these are worn down to the Red Beds for the greater portion of the foundation occurring under the western and southern margins.

These Trinity sands, partially constituting the floor of the plains, can be seen in the escarpment east of Eddy, New Mexico, at Headquarters ranch; the limestone and clay beds of the Comanche series are absent. Most of the sand hills of Texas and New Mexico, which cover hundreds of square miles at the foot of the western escarpment of the plains, I consider to be the remnant of this formation.

Along the western escarpment of the plains and in many of the buttes and mesas of the Canadian valleys the same Trinity sands outcrop again. There is little evidence of their presence along the entire northeast quarter, as shown in the cañons of the Red and Canadian rivers, the plains formation resting directly upon the Red Beds. Wherever this sand occurs immediately beneath the plains formation without the intervention of impervious beds, water will be found in great quantities. At the northwest corner, however, between the Trinity beds and the Staked Plains beds is a great sheet of Dakota sandstone and Denison beds, as seen in Tucumcarri mesa, a remnant of the Llano Estacado.

South of the thirty-second parallel this floor is composed of the rocks of the Comanche series from the Trinity sands to the Caprina limestone, the latter formation constituting by far the greatest area and extending over thousands of square miles in the counties of Midland, Ector, Tom Green, Coke, Glasscock, Crane, Upton, Irion. Menard, Crickett, Sutton, Kimble, Edwards, Val Verde, Kinney, Pecos.

The erosion of the limestones of the Comanche series from the whole region approximately north of the Texas Pacific Railway and west of one hundredth meridian preceding and closing the Great Llano epoch is beyond conception, and we must leave to the purely scientific treatise the discussion of the facts.

The entirely different characteristics of the Llano formation, such as color, composition, and vegetation, render it readily distinguishable from the underlying floor, as seen in the numerous contacts all around the escarpments and in the deeply incised cañons of Red and Colorado rivers along the eastern margin.

As vast as the area of this great mesa now is, it is only a remnant of its former extent, so great and rapid is the process of atmospheric land stripping in the West. There can be no doubt that it continued northward across the valley of the Canadian and other stream as a part of the Tertiary plains of Kansas.

To the eastward its borders extend to the ninety-ninth meridian, having since receded, as it is now receding, by headwater erosion of the streams to its present outline. To the south these plains extend into Mexico and Texas. To the west there is no doubt that these plains extended to Raton Mesa and around the southern end of the Rocky Mountains, south of Santa Fe, on to New Mexico and Arizona. Fragments of it still remain and the Pecos Valley escarpment is traveling east at a wonderful rate.

Neither can there be any doubt but that the Llano Estacado formations covered the great Edwards Plateau, stretching southeastward nearly to San Antonio and Del Rio, now a barren limestone floor, and much of it has since been eroded.

The water of the Llano Estacado.—This vast mesa, with a few exceptions, is singularly void of surface water. It is true that after seasons of rainfall there are occasional ponds or lakes of water in the depressions, but some of these have been known to evaporate during the continuance of a south wind for a day or two. Running Water, in Dickens County, is the only stream on the Llano Estacado, and this really belongs to the marginal rivers of its eastern edge. It has been described by Mr. Roessler as "a bright sparkling stream that suddenly breaks out of the ground, ripples over pebbly bottoms for a distance of 10 miles, and then myteriously disappears like many other streams west of the Pecos River, notably Leon Wells, Comanche Springs, Escondida, Limpia, and Toysh Creek, or the underground river near Castle Mountain in Crane County."

Why this absence of running water over 50,000 square miles of area which posesses a fair rainfall and presents every favorable topographic condition for them? The only answer is that the capping strata of the Llano Estacado are as porous as a sponge, and that every drop of rainfall is either evaporated or taken in and percolates downward until it reaches an impervious stratum. That such is the fact has been borne out by a thousand experiments in the Llano and by the study of its scarp and cañons.

Although considered until the last fifteen years an utterly waterless plain—the largest in America—it is a remarkable fact that over 1,000

wells have been dug into this sheet of strata and water obtained—not of flowing water, it is true, but water which is easily pumped by aid of windmills and which make possible the pasturage of thousands of cattle. These wells have been obtained throughout the whole extent of the vast mesa, and with such success that failure is seldom experienced. Mr. Roessler's statistics show the wonderful distribution of these wells in the counties of the plains in Texas and eastern New Mexico, and there are hundreds more. A study of the drill holes shows that this supply of water comes from the Llano formation in the northern part of the plains, and that it is hopeless to bore into the impervious Red Beds that underlie them, which serve a most valuable function in preventing the farther downward percolation of the water. In the beautiful Blanco and Palo Douro cañons, and all around the northeastern escarpments, the spring line can be seen, where this water of the plain is oozing out at the contact of the Llano formation and the Red Beds. This water is an underground product of the Llano, and from its seepage the supply of the Red, the Colorado, Pease, Wishita, and Brazos is obtained.

This water is stored in the mortar beds and grits of the Llano Estacado formation and is the most remarkable sheet of underground water in our land. Not only is it seen in the heads of the Texas stream, but it follows the escarpment of this mesa up the Canadian 200 miles and around its northwestern point in New Mexico, and thence down the Pecos escarpment again to the Texas line; and you will see many streams and springs flowing out at the line of contact between the Llano formation and the underlying Red Beds. Of such a nature are the Truxillo, the Tucumcarri, the Pajarito, the Portillo, the Alamequada creeks and the springs of the Conejo, Mescalero, Gintrez, and others in eastern New Mexico.

In the southern and southeastern portion of the Llano the well water and springs are obtained from the Trinity sands which at Marienfield and Big Springs are intercolated between the Llano formation and the Red Beds. (See sec. 3, Pl. II.) To reach this sand a slight remnant of the Comanche Peak and Gryphæa beds are first penetrated.

Can artesian water be obtained on the Llano? That the underground sheet water of the Llano beds can be struck throughout the extent of the mesa has been everywhere demonstrated. But it is also apparent that since this water occurs in the surface formation—the Llano beds—there can be no hydrostatic pressure to force a surface flow. But there are other strata underlying portions of the Llano, beneath the Llano water sheet, and to these we have cause to look with much hope that they may present favorable artesian conditions. To understand them, however, it is well to carry in mind the discussion of the underlying floor of the plain and to possess an idea of the sequence and water conditions of the Neozoic strata upon which the Llano beds are deposited. These foundation beds are as follows:

3. Colorado Beds	7. Upper sands	Pervious, good.
	6. Colorado clays and lime	Impervious, bad.
	5. Dakota sands	Pervious, good.
2. Comanche Beds	4. Denison sands	Pervious, good.
	3. Chalk limestone	Impervious, bad.
	2. Trinity sands	Pervious, good.
1. The Red Beds	1. Sands and clays.	

Now, wherever the Llano Estacado formations rests on the impervious Red Beds or Colorado clays, the downward percolation of water will be stopped by these formations and they will form a bottom against

which the water will rest and which will confine the water of the lower beds, but if Nos. 1, 2, 3, 4, 5, and 7 should underlie the Llano formation, then water would be percolated downward through them until some other impervious layer is reached.

As I have shown, it is only the northeastern half of the plain in which the Llano beds rest directly upon the nonwater-bearing Red Beds, and that the northwestern and southern portions are based upon the various beds of the Trinity, Comanche, and Dakota, which, outcropping along the western border, incline eastward beneath the plain, and may serve as artesian water-bearing beds. This relation of the floor to the plain is shown in the accompanying figures.

Furthermore, it has been observed that the water in the Llano formation does not rise under pressure in the well tube, but according to Roessler "nearly all the wells dug or bored through the Comanche limestone into the Trinity sands around the southern edge show a tendency to rise above the point where water was first reached. In some localities a rise of 20 to 30 feet was observed, showing that the supply is under considerable pressure."

Without committing myself to prophecy, it is my opinion that when the portion of the Llano along the Texas-New Mexican line is thoroughly prospected, somewhere in that region will be found an abundant artesian supply from the underlying Dakota and Trinity sands which outcrop so abundantly at a higher altitude in the northwest escarpment.

VIII.

WATER CONDITIONS OF THE TRANS-PECOS, OR BASIN REGIONS.

The portion of Texas and New Mexico west of the Pecos is a part of the vast region of North America which is known in Mexico as the High Plateau or Table Land, and in the United States between the Rocky Mountains and the Sierras as the Great Basin regions. It is characterized by the occurrence of disconnected mountain blocks, usually trending northward, separated by wide flats or plains, most of which in comparatively recent geologic time were occupied by vast inland lakes, several of which still exist, as the Great Salt Lake of Utah.

The mountains and basin plains of this region are popularly confused with the great Rocky Mountain system and the plains of the Llano Estacado and Raton Plateau types. This confusion is a serious error, however, for the great Rocky Mountain mass abruptly terminates south of Santa Fe, and is succeeded by the isolated and disconnected masses described in our chapter on the water conditions of the mountains, while the basin plains, instead of consisting of the coastward inclined stratification of the Llano Estacado, are fresh-water sediments deposited in the intramontane valleys.

This basin region was well defined by Major W. H. Emory, U. S. A., in his report upon the United States Mexican boundary in 1856, as follows:

> Between the two great chains, which I have attempted to describe, occupying the western portion of the continent, there are other chains of mountains, so numerous that it is impossible to describe them by words; some are continuous, some are detached ridges, others isolated peaks, rising from the plateau almost with the uniformity and symmetrical proportions of artificial structures. Between them are found basins which have no outlets to the ocean, but are the receptacles of the drainage of

the surrounding watersheds. Of these, the most extensive is the Great Salt Lake in Utah Territory, and the most remarkable for its historical associations and present importance is the present valley of the City of Mexico.

These successions of basins form a prominent feature in the geography of North America, extending two-thirds its length and quite one-third its breadth. They belong to what has been appropriately designated as the Basin system of North America.

Those found near the boundary are Santa Maria, Guzman, and Jaqui—all to the south of the boundary and within the limits of Mexico. The first is fed by the waters of the river Santa Maria, which runs in a northern direction, and Guzman by the river bearing the several names of Casas Grandes, San Miguel, and Janos, the general course of which is also from the south to the north; and the waters of Lake Guzman and Lake Santa Maria are said to unite in seasons of unusual freshets.

The waters of the Rio Mimbres, near the same meridian as Lake Guzman, which take their rise near the Santa Rita del Cobre, run towards that lake, but they disappear in the plain to the north of the boundary before reaching it.

The waters of these lakes, or inland seas, are brackish at all times, but in seasons of drought, which last two-thirds of the year, they become salt and wholly unpalatable. Their shores are covered with lacustrine deposits, and are usually unsuited to cultivation.

Among the most conspicuous of the basins are the lakes Lahontan and Bonneville, in Utah and Nevada, Death's Valley in Arizona, the Mono basins of eastern California, the Organ-Hueco Valley, and the Jornado del Muerto in New Mexico; the valley of the Salt Lakes, the Eagle Flats, and the Toyah-Pecos basin in Texas, and the basin of Presidio del Norte, the plains of Chihuahua, the Bolson de Mapimi; the plains of Lago Aqua Verde, Baroteran, Barreal del Junco, Valle Hundido, Valle Labago Cayotte, and numerous others of Mexico.

It should be borne in mind that these basin plains cover extensive areas, and occupy much of the region, the mountains being almost secondary to them in extent and areal importance.

The basin plains are vast areas of apparently level lands lying between the mountains, consisting of loose unconsolidated sediment derived from the mountains, sands, clays, pebbles, and bowlders, sometimes cemented by white chalky efflorescent earths, which are apparently chemical precipitates. The surfaces instead of being level are really slightly depressed toward the center. The soil and vegetal products are peculiar. The former is often covered with alkaline incrustations, but is usually of exceedingly great fertility when irrigated. It supports a flora of stunted shrubs and grasses, such as mesquite, greasewood, artemesia, and cactus, entirely different from that of the adjacent foothills and mountains. Along the margins of these plains are great deposits of bowlders brought down from the mountains by the freshets, and covered with the peculiar yucca, sotol, istle, and other fibrous plants.

The basin valleys are usually void of surface streams, and the few water courses in the region are either slovenly flows that have no outlet, but disappear by imbibition and evaporation in their lower courses, or, like the Rio Grande and Colorado of the West, derive their waters from the mountains and merely flow through the basin region but do not originate in it.

Were it not for the mountains there would be no streams upon the basin plains, for all the water is derived from the precipitation upon the former, and is quickly drank in by the porous soil of the latter, thus constituting that class of streams known as "lost rivers."

The Rio Grande is by origin a Rocky Mountain stream, which originally emptied into one of the now vanished lakes, and after leaving the mountains and plateaus south of Albuquerque flows in the beds of these ancient basins, for nearly 300 miles, to the Quitman Mountain group of Texas, through which, in late geologic time, it has cut an out-

let to the Gulf. The "passes" of the Rio Grande at Selden and El Paso are cut through the barriers between the former chains of lakes, now represented by the Jornado del Muerto plain, the Mesilla Valley, and the Organ-Hueco Valley respectively.

The Organ-Hueco Basin.—One of the most extensive and characteristic of these great inner mountain basins of the Tertiary sediment is that lying between the Organ-Franklin and Hueco-Sacramento ranges, in extreme western Texas and southern New Mexico.

This is a vast expanse of apparently "dead level" plain extending from the Rio Grande between El Paso and Fort Hancock, northward some 150 miles. It is 90 miles in width at its southern end, narrowing to less than 40 at its northern. The Rio Grande cuts through its southern end, exposing a grand section of the structure from El Paso on its western side to Fabyan Station on the eastern. This stream has grooved a channel from 200 feet in depth east of El Paso to 500 feet near Fort Hancock. The basin, although apparently level, slopes southward, according to the White Oaks Railroad profile, from 4,500 at its northern end to 3,500 feet at its southern end.

On all sides this flat or basin (locally called "mesa" at El Paso) is surrounded by high mountain blocks, including the Juarez and Mexican mountains on the south, the Franklin Organ and San Andreas blocks on the west, and the Sierra Blanca, Hueco, and Sacramento ranges on the east; all composed of hard impervious metamorphosed limestones, quartzites, granites, and lavas.

The basin proper is unmarked by a single drainage arroyo or channel except the Rio Grande and its laterals. The soil is a pink-gray sandy loam resembling that of the Llano Estacado, and is the residuum of the substructure of stratified, alternating, or unconsolidated sands (grits), clays, and water-worn gravel, often cemented by the white chalky-looking material known in the region as tierra blanca, or white earth.

This substructure of this basin formation is beautifully shown in the river escarpments or mesa east of El Paso, where the typical tierra blanca can be seen capping the scarp, and in the bluffs along the railroad between Etholen and Fort Hancock, where the soft disintegrating escarpment has every aspect of the typical bad land formations of Dakota.

The beds, like those of the Llano Estacado, are chiefly marked by their excessive lack of unconsolidation, the sands, clays, and gravel being almost as loose as when first deposited. White chalky lime strata resembling the Cretaceous beds are numerous, but upon examination they are always found to be conglomerates composed of débris of the jeso and chalk beds, red beds, and cretaceous, mixed with the mountain rock débris.

These beds are clearly laid down in the mountain trough or valley by lake sedimentation, and stream deltas are of newer and later age and never enter into the mountain structure, but are deposited unconformably, like a matrix, upon and around them, having a floor of impervious mountain rock (see plate 1, fig. 6). The thickness of the sediments would be difficult to estimate, but it varies from zero at the mountain edge to at least 1,500 feet in thickness in its southern center.

The northern end of this valley or basin presents several peculiar phenomena; the principal of which are the celebrated white sands. These are composed of rounded grains of gypsum instead of silica, and throughout their extent water is easily secured by digging a few feet.

The extreme northern end of the valley has been covered by a great flow of lava (or malpais) which it is alleged flowed down the valley some 30 miles from the craters of township 10, range 10, first standard parallel. This flat of valley has not upon its surface a single running stream or even drainage basin, and its surface is the most complete picture of aridity imaginable; yet, beneath it lies an illustration of one of the most important water principles in the west.

Franklin basin is surrounded by many terrace benches. These are of two kinds: Remnants of ancient shore lines and delta deposits of débris brought down by floods from the mountains. The terraces are especially well shown in the pass of the Rio Grande at El Paso, where on the western side, seven or eight tiers of them above the river levels can be traced. From the mountains which surround it on all sides considerable water is conducted to the margin of this basin plain, but it sinks almost immediately into its porous soils, percolating downward until resisted by the floor of impervious mountain rock which underlies it. At the northern end many of these mountain streams are perennial, and are good illustrations of the lost rivers of the west. The Rio Tularosa and the Tres Rios flow great volumes of water during the winter and autumnal seasons (precipitation upon these mountains being far greater, perhaps three-fold, than upon the plains), the latter being estimated at 8 annual inches. Immediately upon leaving the impervious mountain rock and upon reaching these plains these streams completely disappear, a phenomenon which can not but impress the observer with astonishment. They do not evaporate, as has been alleged, nor do they sink into caverns, as most people think, but they are imbibed, literally drunk up by the soft sponge-like formation of the plain, and are stored below the line of saturation. The shedding of its rain waters by the impervious mountain rock and its imbibition by the spongy plains rock is the key to the whole water question in the arid region.

The occurrence of the great amount of underground water in the Franklin-Hueco basin formation, at 200 feet beneath the surface, has suggested to many minds the possibility that beneath this there are other porous strata containing water, which sufficient hydrostatic pressure would force to the surface in the lower (Rio Grande) end of the valley. The structure of the ancient lake sediments is composed of alternate pervious and impervious layers of sand and clay beds, and these must have been more or less nested, one within another, in conformation with the topography of the ancient lake bottom, as shown in Pl. I, Fig. 6, affording good containing conditions for artesian water.

The great elevation of the northern end of the valley (where most of the water is received) above the lower is also favorable for artesian conditions, and finally, the fact that nearly all the artesian water in the arid region has been secured under identically similar conditions for similar basins, proves that the conditions for artesian water are at least worthy of thorough experimentation.

Wherever upon this apparently sterile plain an experiment has been made, abundant water has been secured at depths below 232 feet, and windmills pump it for irrigation. The record of these wells demonstrates the storage of much water below the line of evaporation in the deeper strata of the old lake sediments of the mesa.

The following record has been kindly furnished me by B. D. Russell, of El Paso:

Log of wells on Lanoria mesa.

*	No. 2. *a*	No. 3. *b*	No. 4. *c*	No. 5. *d*	No. 6. *e*	No. 7. *f*
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Clay	25	10	8	9	12	10
Sand	32	30	*g*45	20	15	28
Clay	10	15	10	18	60	15
Sand	28	40	20	30	25	30
Clay	35	10	15	15	35	22
Sand	15	25	25	45	14	40
Clay	20	8	20	10	32	27
Sand	12	25	15	30	17	36
Clay	23	15	30	20	....	19
Sand	25	30	10	35	....	13
Clay	15	20	22	....	....	....
Sand	14	8	75	....	....	....
Clay	....	6	10	....	....	....
Sand	....	20	40	....	....	....
Clay	....	....	4	....	....	....
Sand and gravel	....	....	80	....	....	....
Clay "stiff"	....	....	10	....	....	....
Sand	....	....	60	....	....	....
Clay	....	....	36	....	....	....
Sand	....	....	35	....	....	....
Clay	....	....	15	....	....	....
Sand	....	....	35	....	....	....
Sand rock	....	....	1	....	....	....
	254	262	621	232	210	240

* Gravel.

a At 230 feet struck water.
b Water at 256 feet.
c Gravel, first water at 220 feet; second water at 539 feet, rising to 65 feet of surface.
d Water at 212 feet.
e Water at 193 feet.
f Water at 227 feet.
Location T. and P. surveys.—No. 2, sec. 1, T. 2, B. 81; No. 3, sec. 10, T. 2, B. 81; No. 4, sec. 1, T. 2, B. 81; No. 5, sec. 10, T. 2, B. 81; No. 6, sec. 19, T. 2, B. 81; No. 7, sec. 38, T. 1, B. 81.
In well No. 4, after piercing sand in 28 feet of water, the same sunk to original level. Water in all wells rises from 15 to 20 feet after being struck.
g Or gravel.

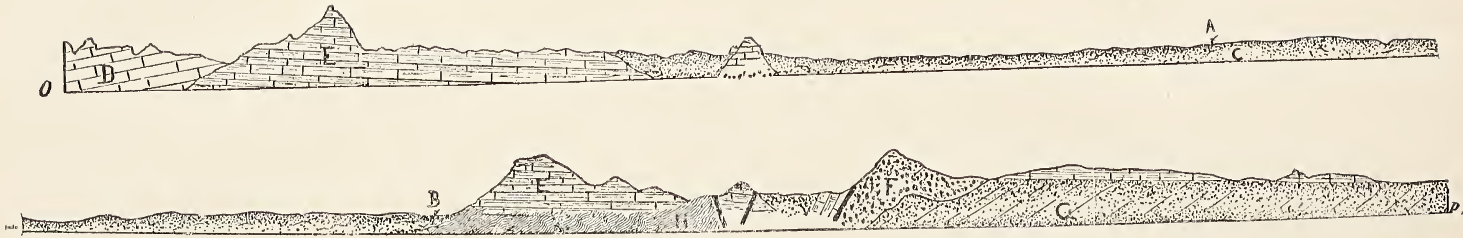
The success of these wells, together with their inexhaustible supply of water, demonstrates the fact that the capacity of the Franklin-Hueco basin formation for water is very great, notwithstanding the slight rainfall and excessive evaporation which has driven the line of visible moisture nearly 150 feet below the surface.

Relatively speaking this basin is one of the great water-bearing areas of the West, where, if irrigation can be profitably conducted by pumping, an agricultural community will eventually thrive. Already several large fruit farms are being irrigated on this basin by means of pumped water, and if they prove profitable there is no reason to suppose but that much of this country, apparently a hopeless desert, will be made into a fertile region.

The Mesilla Basin.—West of the Organ Franklin Range, there is another extensive basin, which is occupied by the valley of the Rio Grande, and extends from near Old Fort Selden to near Frontera, 4 miles west of El Paso. On the west this basin is bounded by the Organ Mountains and other small mountain blocks running north towards the Fort Selden eruptives.

In the basin are situated the towns of Mesilla and Las Cruces, two of the most flourishing places in southern New Mexico, and extensive agriculture is carried on by irrigation from the Rio Grande.

The formation of this basin is the same as that of the Hueco-Franklin basin, and at times no doubt its lakes were continuous with its waters. The river which is in the consolidated mountain rock at Fort Selden, has cut deep into this plain, and much of its waters are imbibed by the



A, Southern Pacific Railway. B, Texas Pacific Railway. C, Post-Cretaceous deposit (no rock struck at 1,050 feet). D, Cretaceous limestone. E, Carboniferous limestone. F, Conglomerate of Metamorphic and Serpentinous rock cemented by ferruginous silico-calcareous matter. G, Red Sandstone. H, Talcose and Mica Schist.

Section Across West End of Eagle Flats, Illustrating Basin Deposits between Mountains. Copied from W. H. Van Streernwitz.

porous formation until it again enters the mountain rock some 100 miles below at El Paso.

The surface character and water experiments conducted in this basin have been ably described in the report of the Senate Committee by citizens, as follows:

From the lower end of the Jornada at Fort Selden the Rio Grande again broadens out into a beautiful valley. It is a basin in shape. Both to the east and west are the mountains, which close in at Fort Selden on the north, and at El Paso on the south. The length is about 40 miles. The Organ Mountains, 12 miles from the river, from the eastern rim of the basin. It would require a further examination to show if the other conditions of an artesian basin are present.

No deep wells have been attempted. The deepest reported is 65 feet, but from these wells of moderate depth water rises nearly to the surface. The following letter from Mr. John De Meir, a citizen of Las Cruces, shows the experience at that point.

"I am convinced that our valley is one immense artesian belt, and will cite a few cases to confirm it.

"The deepest drive well here is 65 feet, at Col. Albert Fountain's. The water stands at 4 feet of the surface. Maj. Llewellyns well, 700 feet distant and south of Fountain's, is driven 45 feet; water stands at 4 feet. One mile south of his well, McClure Brothers drove down 65 feet; water stood at 4 feet. They broke their pipe and could drive no further. An open well up on the foothills, upper part of town, sunk to a depth of 45 feet, and the bottom being about 12 feet below the valley land, gave a poor supply of water. Mr. Ackenback, the owner, drove a pipe 16 feet in the bottom and it rises in the well and yields all the water they desire. So far the strata here is the same as in California. In driving wells every few feet they strike a hardpan that makes it slow, hard work until it is penetrated, and when passed through it will drive easily till next hardpan is struck. These stratas are from 2 to 4 feet thick, and in sinking open wells it is necessary to use explosives. I have been hammering at the people for the past year to raise funds and give it a trial, and while all are of the same opinion as I am, it is slow work to get them to move in the matter. On the east side are surrounded by a high mountain range 2,500 feet higher than the valley, while on the west we have a high mesa and mountains. At Fort Selden the mountains meet and form a narrow pass worn through the rock, and at El Paso they meet again and form another pass, so that we are truly a basin with a rock pass above and below us. I send a diagram, which may give a better idea of our situation."

Mr. De Mier, of Las Cruces, says: "About 28 miles above here, in upper end of this valley or above it proper, springs crop out at river bank and keep the lagoons full when Rio Grande is dry. Am informed same feature prevails this side of El Paso, Tex., at lower end of the valley. There are immense bodies of water flowing from hidden veins in the Organ Mountains 12 miles east of this point; one in particular is over 50,000 gallons an hour. At the Memphis mine that amount was pumped day and night for over a year. It came in at about 130 feet in the shaft, and only part of it entered the shaft. Mine has been closed down for past six years on account of water. There are a number of springs on both sides of the range, mostly on west side, draining into this Mesilla Valley.

The structure of this valley is also favorable for the imbibition of all the water that falls upon it, or that flows down the adjacent mountain sides, while the presence of the running water of the Rio Grande throughout its length has obviated the immediate necessity of experiments, like those at La Noria which resulted in the discovery of the Franklin-Hueco water bed. There can be little doubt then from the data obtained but that well water can be obtained anywhere throughout this basin.

Covering the artesian possibilities of this region, it can only be said that it presents the same features as the Hueco-Franklin basin, to wit: A sharp topographic slope from the north end, where most of the water is received, to the south, and a general similarity in structure to the conditions of the similar basins of the San Luis and other places.

It may also be added that, extending southward from the Donna Ana to the Florida mountains, there are extensive dikes or walls of igneous matter which are apt to have a negative effect upon artesian principles in the western part of the valley.

The Jornado del Muerto basin.—The western end of the Mesilla basin

or plain is terminated by a group of stratified and volcanic hills, which extend westward from the Organs, via Dona Ana and Fort Selden, cutting off the Mesilla basin from that of the Jornado del Muerto, which begins north of this barrier and extends northward for a hundred miles. This is perhaps the most noted of the basin plains, having long been celebrated for its absolute lack of surface water, and lying directly in the track of the ancient Santa Fe-El Paso trail. Its very name signifies the journey of death, and was given it owing to the great difficulty travelers found in crossing it.

The Jornado occupies the country north of the Dona Ana hills from Rincon northward. On the east its limits are the San Andreas and Sierra Oscura, the northward continuation of the Organ range. On the west, by the Sierra de los Caballos and Fra Cristobal, the southern continuation of the Sandvia range. The Atchison, Topeka and Santa Fe enters it at Socorro, northward, and continues upon it to Lava station.

This basin has been described by Dr. G. G. Shumard * as follows:

It lies east of the Rio Grande and may be described in general terms as a gently sloping plain, somewhat elliptical in form and inclosed on both sides by lofty mountains. This plain extends from near the southern extremity of the Dona Ana mountains, northwest, for the distance of 80 or 90 miles, and varies from 12 to 40 miles in width. Near the southern extremity it is partly interrupted by the Donna Ana mountains, and there its width does not exceed 12 miles; but as we travel north it rapidly widens, attaining its greatest transverse diameter at the distance of 20 or 25 miles; it then gradually diminishes until we arrive at the northwestern extremity, where it does not exceed 18 or 20 miles in width. Throughout the entire length it is marked by a distinct central depression, which, as will be seen hereafter, corresponds pretty accurately with the synclinal axes of the underlying strata.

Wherever examined, the surface formation was found to consist of detritus of rocks débris, in all respects the same as those composing the neighboring mountains from which it was doubtless mainly derived. The precise thickness of this deposit could not be very accurately determined, as only a few natural sections were observed, and these only near the base of the mountains. In two localities its observed thickness was nearly 500 feet.

The two ranges of mountains forming the eastern and western boundaries of the Jornado de Muerto curve gently in opposite directions and are remarkable for their close general resemblances and simplicity of structure. In each we find a gentle slope toward the plain and bold and nearly vertical precipices in the opposite directions. Along their summits are exhibited the sharp and jagged edges of their uplifted strata.

The range of the east varies in width from 5 to 15 miles, and forms a nearly continuous range extending north and south, the entire length of the Jornado, as will be hereafter seen; it is composed principally of upheaved strata of dark gray, blue, and black subcrystalline limestone, dipping west at various angles. Although these mountains have the same general direction, and are apparently continuous with the Organ range with which they have been heretofore classified, nevertheless their general conformation and structures are totally distinct. In no respect is there the slightest resemblance between them, one being composed almost entirely of sedimentary strata, and the other mainly of eruptive rocks.

Upon the western side of the "Jornado" the mountains are interrupted at their northern and southern extremities by broad valleys, the main portion of the range being separated in the one direction from Fra Cristobal Mountain by an extensive volcanic district, and in the other from the Rolledo Mountain by the valley of the Rio Grande and a chain of igneous hills. Although in general appearance very closely resembling the mountains, upon the opposite side of the plain the central portion of this plain is found to differ somewhat from them in composition, the limestone being here overlaid by grits, shales, and sandstones, which altogether present an average thickness of about 800 feet, and are uniformly found dipping towards the east. The length of this portion of the range is from 40 to 50 miles.

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* The geological structure of the "Jornado del Muerto," New Mexico, being an abstract from the geological report of the expedition under Capt. John Pope, United States Topographic Engineers, for boring artesian wells along the line of the thirty-second parallel, by Dr. G. G. Shumard, M. D., geologist of the expedition. (Transactions of the Academy of Science, of St. Louis, Vol. I, 1856–'60, p. 341.)

Geologically speaking, the Jornado del Muerto may be considered as nothing more than a single trough, composed mostly of limestones, sandstones, and shales, and covered to the depth of 500 or 600 feet with loose detritus.

As this trough throughout the greater portion of its length appears to be entirely free from igneous protrusions, I am of the opinion that an abundant supply of water can here always be obtained by means of artesian wells. The depth to which borings would have to be carried for this purpose can not very readily be determined, as but few natural sections were exposed upon the plain, and these only extended through a portion of the detritus. But as the Cretaceous standstones overlying the shales of the Coal Measures, which would have to be first passed through, exhibit in the mountains, upon the western side of the "Jornado," an average thickness of about 600 feet, it is probable that water could not be obtained at a less distance beneath the surface than a thousand or fifteen hundred feet.

As the "Jornado," besides its lateral slopes, presents a general one from NNW. to SSE., the most favorable situation for the experiment would probably be along the central depression, marking the synclinal axis of the strata, taking care to avoid on the one hand the igneous protrusions, of which the Donna Ana Mountains form a portion, and on the other, the chain of volcanic hills near the northwestern extremity of the plain.

This description is in general correct, but the writer is of the opinion that if artesian water is found it will be in the detrital deposit of the basin, and not in the underlying floor of mountain rock, and at a much less depth than that indicated by Dr. Shumard.

Probable basins of the Pecos Valley.—The Rio Pecos, from the mouth of Delaware Creek to Pecos City, 50 miles, and from thence to an undetermined point some 50 miles below, flows in marls and clays of the typical basin character, which, together with the topographic conformation and well-boring records of the region, lead me to believe that this portion of the Pecos Valley is either another of the Quaternary basins or an allied estuarine formation.

The main escarpment of the Llano Estacado is far east of Pecos City, and the river is in a wide flat or basin some 30 miles wide, from Toyah to Quito, which seems unlike a drainage flood plain. This flat is marked on the east by a high scarp line near Quito, 12 miles east of Pecos City, but inasmuch as the apparent shore-line formations were of the softer Red Beds and plains formations, instead of the harder mountain rock, like that of the other basins, it is difficult to say after my brief studies whether or not it is a true shore line, although I am greatly inclined to think it is. The western shore of this apparent basin is the east of Toyah against the slope of the Davis Mountains.

Both at Pecos City and at Toyah, numerous artesian wells have been found in this alluvial deposit, be it of lake or river origin, which give weight to my hypothesis that these beds are the chief water-bearing strata of the west. These wells also occur under favorable topographic conditions, *i. e.*, at a lower altitude than the shore line of the basin, and are a remarkable demonstration of the amount of water which under favorable conditions can be abstracted from such an arid region, situated as they are, in a district which one would, under the old mountain theory of water, consider most unpropitious.

Mr. Roessler has reported (1890) the following wells from the Pecos Valley:

Flowing artesian wells at Pecos City, Reeves County.

Owner or informant.	Depth.	Bore.	Cost.	Remarks.
	Feet.	*Inch.*		
J. B. Gibson	250	4	$300	9 gallons per minute.
W. S. Marshall	315	3	500	60 gallons per minute, pressure 20 pounds.
Texas Pacific Railway	220	4	440	Water rises 27 feet above ground.
C. H. Merriman	185	3	351	60 gallons per minute.
W. D. Johnson	185	3	....	Do.
Do	185	6	....	Very light flow.
T. M. Clayton	227	3	....	All these wells are bored within a circumference of 2 miles, and all of them have a continuous flow.
Matheson, Cook & Walker	213	3	....	
Gage, Walthall & Powers	250	3	....	
Pecos Valley Land and Irrigation Company.	237	3	....	
Havens, Phillips & Allen	237	3	....	
Juston Robertson	shallower	2	....	
A. T Windom	...do	2	....	
W. D. Johnson and C. F. Thomason	235	3	....	
County of Reeves	227	3	....	
Chilton, Bowen, *et al*	....	3	....	

These wells are located on section 40, H. & G. N. surveys, and section 69, block 4, H. & G. N. The water in all of them is slightly brackish, some being better than others; in one or two some saline ingredients. The water, however, is not injurious to vegetation, and in a small way is used for irrigating gardens, though most of it is allowed to run *ad libitum* and make a mud puddle of the vacant town lots.

Flowing artesian wells at Toyah, Reeves County.

Owner or informant.	Depth.	Diameter.	Cost.	Remarks.
	Feet.	*Inches.*		
Texas and Pacific Railway	834	* 9 † 13	....	300 gallons per minute, or 432,000 gallons per diem.
Do	514	12	....	About 9 gallons per minute. Now being bored down farther.

* Top. † Bottom.

The water from both of these wells is white sulphur with a salty taste, and can be used to advantage for irrigation, as the water does not seem to be injurious.

At Toyah the water is found at 20 to 30 feet. Underneath this, at a depth of about 200 feet, at Pecos, is artesian water under great pressure. Now at Toyah, altitude 2,975, the same water is found at about the same depth and in about the same material, but it is devoid of pressure here. At 832 feet a strong flow (300 gallons per minute) of sulphur water was obtained. (It is claimed that the sulphur came from some higher point in the well and that the bottom water was pure, and that the present outflow is impregnated with sulphur only because the casing was defective.) It is probable that this same water will in all probability be found at Pecos at a similar depth. Adding to the pressure existing at 200 feet, 300 gallons per minute through 3-inch pipe, the weight of a column of 375 (the difference in altitude between Toyah and Pecos) it is easy to presume that at a depth of 1,000 feet artesian wells can be obtained which will flow from 1,000 to 2,000 gallons per minute.

The wells of this subdistrict as a rule are very deep and the water in many of them is practically unfit for use.

It is my opinion that these wells can be obtained over about 100 square miles of this region, from 50 miles north of Pecos City to 50 south, and will prove a great blessing to the region.

It is interesting to note that laboring under the old theory of mountain origin of artesian water Capt. Pope and Dr. Shumard bored their unsuccessful experimental well just north of the Pecos City basin in the

hard rock, when if they had left the mountain rock out of consideration and bored 20 miles southwest on the supposed unpropitious plain they would have secured abundant water at shallow depths.

The Eagle Flats Basin.—Another and extensive formation lies between the parallel mountain ranges of the Quitman-Muerto series (whicn is a continuation of the Hueco series) and the Diablo Davis series. This basin is of irregular area as shown upon the map, and has two principal arms or members, the southwest of which is traversed throughout its greatest length by the Southern Pacific Railroad from the Sierra Blanco to Marfa, a distance of 100 miles, and is known as the Eagle Flats. This is a very narrow basin seldom exceeding 25 miles in width, and like the others is surrounded on all sides by mountain blocks, against which may be clearly discovered the terrace structure of the ancient lake shores. The soil is the same pink tinted gravelly loam of the Franklin basin.

This basin has never been explored for water where it could be most expected, *i. e.*, in its lower and deepest end, but upon the contrary, the Southern Pacific has made several very costly experiments in drilling into the hopeless mountain rocks around its edges. It is my opinion that wells similar to those at La Noria on the Franklin basin will yet be obtained in the now desert Eagle Flats.

From Sierra Blanco this basin sends another arm east and northward, up to the east side of the Hueco series, and west of the Carrizo and Diablo mountains toward the Wind mountains, for an unknown distance; the general outline, so far as I have been able to ascertain by inquiry and observation, being as laid down upon the map. In this portion of the basin there are several salt lakes of small area and extent. The Texas Pacific crosses this portion of the area to eastward of Van Horn, where it crosses out of it through a mountain gap.

Valley of the Salt Lake Basin.—Another vast basin extends along the meridian of 104°, from the southern end of the Guadalupe, north of Wildhoyse station on the Texas Pacific. This basin is about 35 miles in extent northwest, southeast, and about half as wide, and is marked by numerous salt lakes. It is surrounded on the west by the mountain blocks of the Sierra Diablo, on the north by the Guadalupes; and on the east and south by low unnamed mountain blocks. From descriptions this must be one of the most interesting of the great basins, but the writer has been unable as yet to visit it. A few wells are reported.

Basin of the Mimbres.—West of the chain of mountain blocks, including the Florida's and Las Mimbres, the Black Range groups on the east, and the Sierra Bacco, Pyramid, Hatchet, Burro, and Black ranges in the west; there is another vast basin into which drains the river known as the Mimbres and several other typical lost rivers, most of which come from the Mimbres and Black mountains.

This basin with its southern extension—the Florida Plains—includes about fifty townships or 9,000 square miles in the United States and at least as many more in Northern Mexico.

Its surface and formation is composed of the same level topography and lacustral débris as the other basins mentioned, and like them it has a drainage slope southward.

The Atchison, Topeka and Santa Fe, the Southern Pacific, and the Silver City and Pacific railroads, all traverse this valley and meet at Deming, which is situated near its eastern border.

The northern end of this valley receives, relatively speaking, much mountain water from the Black and Mimbres ranges, and, like the Franklin Hueco basin, is characterized by numerous lost rivers. One

of these, Las Mimbres, is the most conspicuous of all the lost rivers of the West, and has been the cause of much speculation and wonder. It is a bold flowing mountain stream until it gets well out upon the plain, when it completely disappears by imbibition and evaporation.

Much of this water, as in the other basins, becomes stored in the sponge-like strata of the old lake formation, and is readily accessible in many places, especially at Deming, where irrigation is produced from this so-called "underflow."

According to the testimony of Mr. Warren Bristol, this county (report of special committee, United States Senate on Irrigation and Reclamation of Arid Lands, Vol. 3, p. 64) formerly appeared before the discovery of this underground water as a barren plain; a desert with nothing but sparse grama grass growing upon it.

At that time there was no water on this table-land, except occasionally, when the water came down by flood. No water was known to exist there, but there is a region of country from 25 to 50 miles long, north and south, that we know of (and how much farther it exists we do not know) where if you dig down anywhere you will strike water about 50 feet in inexhaustible quantities. To illustrate: At my place I have a powerful windmill, an 18-inch wheel (Holladays). Each revolution of that throws out 100 gallons of water; you can run it up to 160 revolutions per minute. There are only $2\frac{1}{2}$ feet of water in that well, and that quantity can not be lowered with pump. It is so all over the plain.

Deming was a very unpromising place; now it has a great many windmills, and is a pretty place. The change really seems like a miracle. The Southern Pacific Railroad Company was the first to discover this water beneath the surface. Since then it has improved; the whole plain I have described is covered with cattle ranches and the ground is all occupied with pumping machines of this kind to water the cattle. A great deal of money is invested there. The whole plain is taken up. In addition to that, the great waste of water that flows out from the foothills onto the plains could now be collected in immense reservoirs and distributed over the plains for agricultural purposes. The opportunities for that are very great.

I have lived in New Mexico for something over seventeen years, and I regard New Mexico as having one of the most healthful climates on the continent. My experience and observation convince me that the most salubrious region is not high up in the mountains, at an extreme altitude, nor down in the river bottoms, where there is more malaria, but out on the plains. I consider this as good a climate as can be found in the world. Wherever water can be had the soil is wonderful in its productiveness. It is rich in all the elements of fruitfulness. On the plains the greatest drawback at present, in my opinion, to successful cultivation is the strong spring winds, which prevail in every section where there is no wind-break. As soon as forestry is systematically cultivated here, and trees are planted so as to break the prevailing winds, it will be a wonderful country with water for productiveness. The altitude of Deming is about 4,000 feet. It is on the first plain of what we call the Mesa Valley of the Rio Grande. It commences on the high bluffs of the Rio Grande, and is a lovely plain all the way on into Arizona.

In addition to the basins mentioned there are numerous others which it has been impossible to investigate, but which lie mostly beyond the territory of these investigations. Among these are several of minor importance, in the so-called phenomena of Texas, west of Texas Pacific Railway; several in southwestern New Mexico, such as the Playas de los Pina, Valle de los Playas, and others, and several in the mountains of north central New Mexico.

The water conditions of the basins in general.—These vast inter-mountain, plains, or basins, or ancient lake valleys have, until lately, been absolutely void of surface water, and so synonymous with sterility that they have been considered often the synonym of death, like Death's Valley in California or the Jornado del Muerto of New Mexico. That they should now be found to be underlain in much of their area by an abundance of fresh water, is a fact which is of greatest value in the economic conditions of the arid region, where water is worth more than land, and where a drop to even quench the traveler's thirst is usually unobtainable, except in rare localities. The far greater extent of these

58.

Characteristic View of the Basin-Plains of Arizona and New Mexico.

[From Report of Mexican Boundary Commission, 1856.]

basins than the mountains over New Mexico, Texas, and Mexico, seems to have been overlooked or considered unimportant by national surveys, as well as its underground water conditions.

As a rule these basins are surrounded on all sides by blocks, or ranges of high mountains, the blocks usually unconnected and through the passes of which many of these lakes may have been once continuous in some period of their existence, but were not so during the latter days. These mountain blocks are more extensive at the northern border of the basin region, and the precipitation is greater upon them as a rule than upon the intervening plains.

Taking the basins as a whole, I think that from a study of their topographic and geologic features, a few generalizations can be deducted which will be of inestimable value to the future investigators of underground water supply of the region.

These lakes belong to a great area of similar features which exist over northern Mexico and the Southwestern United States during comparatively recent geologic time. This area composed much of California, Utah, Nevada, Arizona, New Mexico, and Texas west of the Pecos, and the Nevada Utah portion has been accurately and minutely described by Gilbert, Dutton, and Russell in the monographs of the U. S. Geological Survey, as the basin region of the United States. These basins, as is testified by all who have visited them, are often dry while frequent storms and cloudbursts can be seen upon adjacent mountains.

These basins, at least in New Mexico, Arizona, and western Texas, although originally horizontal, have all been elevated to the northward, so that old lake bottoms now incline southward, or southeastward at a considerable gradient.

In composition they consist of exactly the same material as the mountains, but under different physical conditions. In the mountains this rock is massive, imporous, and impervious. It was ground up, pulverized, and assorted by the waters before its deposition in the lake basin. This difference in physical condition is radical, and in the consideration of underground waters it is all important. A cubic foot of massive glass would contain little rock water, even if soaked for days, and the mountains are composed of just such material. The same glass if ground to small grains would become porous and absorb into the interstices between them from one-tenth to one-half their volume. The mountain rock was ground before it was distributed over the valleys, and hence, although the same materials as the mountain rock, it has become porous, and, as these old lake sediments, will imbibe and retain the water a hundred fold.

The water falls mostly upon the mountain. Some of it is imbibed by the small patches of soil and porous layers or penetrates the fissures and caverns to be more slowly returned to the surface in after times. A good amount is also evaporated by the wind and the intensely heated rock. Most of the rainfall, however, flows off in the floods down ravines and cañons towards the base level, which is the surface of the basin plain. Upon reaching this, part of the stream is imbibed or drank in by the porous cavernous sands and loosely cemented soil, and a great deal of it sinks beneath the line of saturation, between which and the hard rock floor, upon which the basin formation is deposited, water is stored as shown in the previous figures.

This water of the basins is always available by bored wells, but it may or may not possess artesian pressure, according to its stratification and topography.

If the basin formations are composed of alternations or bands of sand and clays, in other words stratified (and most of them are), and these water strata have inclination, which they usually do, in concave or synclinal nested arrangement, then the stratigraphic conditions for artesian water are mostly ratified, as at Toyah, Pecos City, and elsewhere. If this stratification is more or less concave or nested, and there is a corresponding topographic inclination from the edges towards the center of the basin, or a slope from one end of the basin to the other, topographic conditions for artesian water will also be favorable, and experiments should be tried near the central portion of that end of the basin which is lowest in altitude, provided there are no unfavorable conditions, such as dikes or fissures.

The writer is inclined to the belief that in all of these flats or basins water can be obtained in quantities that will at least do for stock purposes and possibly for limited agricultural use. Everywhere that wells have been sunk (save in the exceptional places such as at the immediate edge or at the higher ends, as at Sierra Blanco) water has been obtained, and at La Noria, 10 miles northeast of El Paso, there are several fruit farms in the midst of the plain being irrigated by water pumped from wells in the basin formation at depths of 200 feet. I have been informed that waters rose 150 feet under hydrostatic pressure above the bottom of a 600-foot well at this place, thus indicating possible artesian pressure at lower altitudes.

In endeavoring to obtain water upon these basins, several important things are to be avoided.

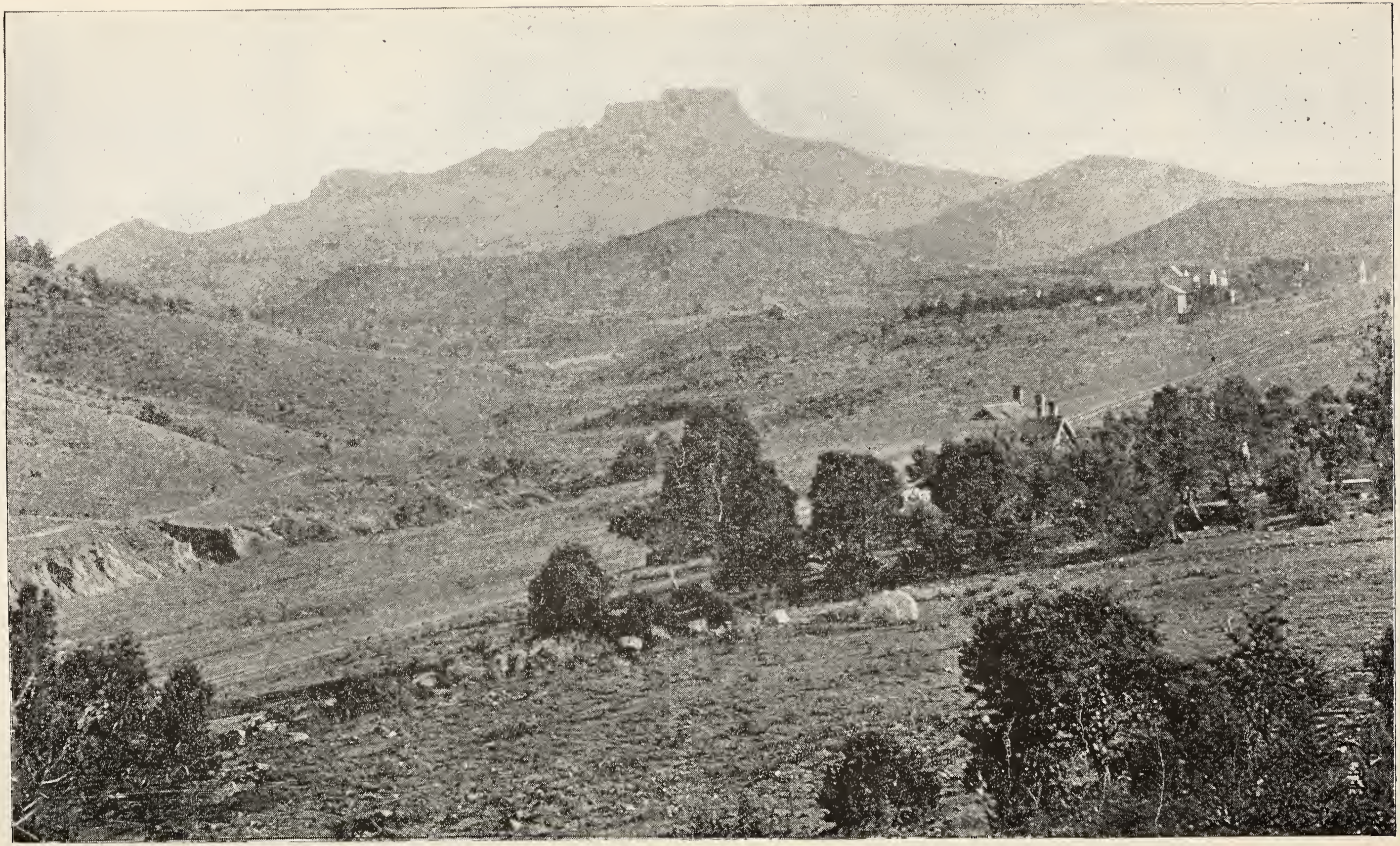
1. Boring too near the edge or perimeter of the basin. Inasmuch as the soil is usually dry for a distance of 50 to 200 feet; and that the floor of the basin formation is composed of impervious mountain rock, the edges of the basin are not apt to be in the saturated portion of the basin formation at all; but the unpropitious formation of the mountain rock will be reached.

2. Boring near the upper or higher end of the basin. Most of the basins are higher at one end than at the other, often by a thousand feet or more. This is a product of the elevation they have undergone since their beginning. It is obvious that the surface water would drain downward and toward the lower portion of the basin, and that the upper end would usually be unsaturated. Many thousands of dollars have been lost by railway companies and individuals by boring for water too near the edge or upper end of these basins and many regions erroneously adjudged void of water on account of such failures.

3. Boring through the basin formation into the mountain rock floor. It has been the experience of most drill holes that it is useless to expect water in the hard rock floor underlying the basin formations, and when this is reached, except when there are very favorable conditions of porosity and inclination, further boring is useless.

The quantity of available water of saturation varies in different basins, and is proportional to the area and rainfall of the surrounding mountains. The San Luis Valley of northern New Mexico is surrounded by high mountains of vast drainage area, larger than the area of the valley. These mountains are covered by snow in winter and have greater rainfall than the mountains of the southward, and the amount of water drained onto and imbibed by the basin is enormous. The Sierra Blanco Basin, on the other hand, is encircled by comparatively low untimbered mountains, upon which there is little precipitation, and no great supply of water could be penetrated.

It is not probable or possible that sufficient underground water is



FISHER PEAK, TRINIDAD, COLORADO.

Showing structure and erosion of Las Vegas-Raton Plateau, the highest block of mountain being of lava.

stored in these basins for a large or extensive agricultural population, but when it is remembered that water for even the passing traveler is lacking, and that many of those vast areas of land are almost absolutely uninhabited for want of water, even a single well to every 20 square miles would be of more value to the region than a vast lake of water is now in the humid regions; and it is safe to predict that in a few years there will be hundreds of wells to one at present, around many of which will be not a few valuable irrigated farms.

The possible success of artesian water in these basins is also suggested by the fact that numerous artesian wells have been struck in similar basin deposits in California, Colorado, and Utah, and as I have been informed in the basin valleys of Atacayma in Peru and the valley of Mexico. In fact no case of artesian water having been struck in the arid region from any other supply than these unconsolidated basin or allied deposits has ever been reported south of Dakota* and west of the Pecos.

In fact the newer deposits, whether lacustral, littoral, or fluviatile, have ever proved the most profitable source of artesian water in this country, even in the humid region, as at Memphis, where magnificent wells are secured from the Orange sand and bluff deposits. A noteworthy fact also about many of these wells, as at Roswell, N. Mex., Memphis, Pecos City, and elsewhere, is that they occur in regions which under the old theories of upturned mountain rock, synclinal basins, etc., would have proven entirely unpropitious.

IX.

WATER CONDITIONS OF THE MOUNTAIN REGIONS.

The vast area discussed in this paper is preëminently a region of plains, the mountain proper forming but a small proportion of the whole, and of much less consequence in relation to underground water supply than is popularly supposed.

There are only two classes of mountains proper within the region, those of the Wichita and Arbuckle groups in central Indian Territory and the isolated basin ranges of the Trans-Pecos region.

In the popular classification every butte, mesa, hill, and escarpment is termed a mountain, but nowhere east of the Pecos, except in Indian Territory, is there a true mountain, or protuberance, which is the product of the folding or other distortion of the earth's strata. The so-called mountains of central Texas are buttes and mesas, composed of remnantal patches of horizontal strata, described in our chapters on the Grand Prairie and Central denuded region. The alleged mountains of Burnett and Llano counties are likewise mostly of this type and occupy an erosion valley in the plateau of the Grand Prairie.

The true Rocky Mountains constitute the western limit of this investigation, and it is a current supposition that they are the receiving area for all the underground water between them and the Gulf.

Although the most conspicuous feature in all North America, topographically, the southern extent and limitations of the Rocky Mountain ranges have been poorly defined. Their eastern border or foothills,

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* The Dakota artesian basin is in a semihumid region, though it is probable that it will be extended westerly into the arid area.

where they join the plains, north of Santa Fe, N. Mex., to the British line, is unmistakably one of the sharpest and best known features of our country, but no geographer has yet defined their termination south of Santa Fe, and the numerous but entirely different mountains of the basin regions of New Mexico, west Texas, and old Mexico are always confused with them.

Prof. J. J. Stevenson, in his valuable report upon the geological examinations in southern Colorado and northern New Mexico, during the years 1878–'79, has admirably described the Rocky Mountains near their southern terminus and shows their type of structure along their eastern front, from Gallinas to Pueblo, to consist of excessively folded and broken (faulted) strata, conforming to the popular description of having been "upturned."

South of the latitude 25° 20′, he says: "The region is a vast plain cut into mesas, which Prof. Newberry identifies with the Llano Estacado or Staked Plains of Texas," but which in fact should be classified with the plateau region to the west. Towards the south and southeast the dips of this plateau are very gentle, for the most part southward; towards the Rio Grande the plain is broken by the basins and "lost ranges," of which the Placer and Sandia mountains may be taken as types. These short isolated ridges lie west of the Santa Fe axis, and seem to bear no relation to that disturbance whatever. The Archæan area of the Santa Fe axis ends abruptly at about 9 miles north from Gallinas, and a fault is easily recognizable along its eastern side.

South of the Plateau region which encircles the southern end of the Rockies, the country is that of the basin region elsewhere described, consisting of vast basin plains, surrounding isolated and lonely mountain blocks. The mountains are not part of the plains, as in the Rocky Mountain and Plateau regions, nor are the strata of the plains associated with them or bent up at their edges as geologically and popularly supposed, but a newer and later deposit is laid down against them and is composed of débris of the mountains (see Pl. I, Fig. 6).

The foothills or hog-backs, consisting of vertical strata which accompany the whole front of the true Rockies, likewise end with them.

Many of these mountain blocks have no names at all although large in size. The following, however, are the most conspicuous:

In New Mexico: The Sandia, Organ, Oscura, Jiccarillas, Florida, San Andreas, Guadalupe, and Sacramento.

In Texas: The Franklin, Hueco, Guadalupes, Diablo, Davis, Van Horn, Carrizo, Los Chisos, Sierra Blanca, Apaches, and Santiago.

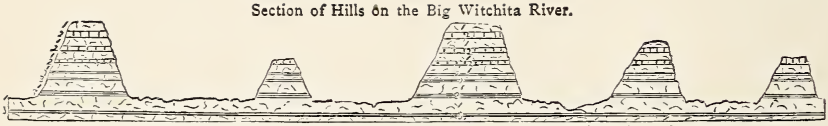
In northeastern Mexico: Juarez, Sierras Rica, Blanca, Frailes, Hornigas, Cuervas, Pinto, De Aire, Del Carmen, Los Burros, Menchaca, Apaches, Picochos, Gomas San Marius, Azul, Lampasos, Trinchera, Fragna, Catorces, and many others.

Nearly all of them consist of elongated masses, extending approximately north and southward, and are mostly composed of hard, impervious quartzites, limestones, and igneous rocks, which have little capacity for imbibition of rainfall, the latter usually flowing away rapidly upon the adjacent basin plains.

The Guadalupe Mountains, which are the most eastern of the groups, are somewhat different and are composed mostly of hard Carboniferous limestone, the water conditions of which are discussed in another chapter.

This group corresponds more to the strike of the main Rocky Mountain axis than any of the others, but they are entirely isolated from them.

Section of Hills on the Big Witchita River.



1. Red Marly Clay. 2. Saccharoid Gypsum. 3. Finely Laminated Sandstone.

[After Shumard.]

The great height and conspicuousness of these mountains, and the excess of precipitation upon them, together with the old superstition that upturned mountain strata are the source of all artesian waters, has led many people to believe that from them alone must be expected an artesian supply. Following this belief, thousands of dollars have been expended, especially by the Southern Pacific Railway Company, in drilling for water at the base of these mountains, while the Government experiments under Capt. Pope were made upon the same hypothesis.

A brief examination of the structure of nearly any of these mountain blocks should dispel the idea that they can ever be the source of great artesian supply. Not only are the rocks impervious to moisture, but the stratification is excessively inclined, and broken by the frequent dykes of eruptive material, which would prevent the transmission of water. With the exception of the cavernous limestone region of the Guadalupes, there are few running springs in all the great territory covered by these streams. No better proof of the unfavorable artesian conditions of these mountains can be given than to cite some of the numerous failures which have resulted.

No idea can be more fallacious than the one generally entertained that the underground waters of the Texas-New Mexico region are in any manner supplied by the Rocky Mountains, for the geological structure is such as to absolutely prevent such a possibility, for the great fault lines and valleys of erosion of the foothills break the continuity of stratification and make such underground transmission impossible. The only water from the Rocky Mountains that reaches the regions under discussion is the surface drainage of the Rio Grande, Pecos, and Canadian.

The Mountain masses of the Basin range are equally unimportant relative to the water supply, although likewise erroneously considered as the source of much underground water.

These isolated ranges, which succeed the Rocky Mountains toward the south, are numerous and of vast proportions, occupying the whole of the country of northern Mexico and the United States from the Pecos to the Sierras, and constituting with the intervening plains the great Basin region of North America, the isolation becoming more and more complete to the southward and the basins more extensive. These mountain blocks, with their accompanying basins and aridity, extend southeastward in Mexico almost to the Isthmus, the Rio Grande below the mouth of the Pecos approximately marking its eastern border.

The first and most conspicuous of these were the Government experiments under Capt. Pope and Dr. G. G. Shumard, in 1858. They selected a site in the Pecos Valley, 8 and 14 miles east of the river, near the Texas New-Mexico line, beneath which they had determined the mountain rock of the Guadalupes to extend. After boring 850 feet, and reaching far down into the mountain limestones, the wells were abandoned as failures.

The Southern and Texas Pacific railways had spent thousands of dollars in seeking water in the Trans-Pecos region, and in every instance where they penetrated the harder or mountain rock their experiments have proved failures, as will be seen in the statistics from Mr. Roessler's report, and in no case were flowing wells obtained.

THE RATON LAS VEGAS PLATEAU.

The general conception of the Rocky Mountain region, based upon the familiar conditions seen at Denver, is that the plains formation

extends to the base of the mountains, and that its strata incline coastward or away from the mountains, affording ideal conditions for the transmission of Rocky Mountain water to the whole of the coastward country.

South of the Colorado line, however, in northeastern New Mexico and to some distance north of Trinidad, exactly the opposite condition exists, for around the southern end of the Rocky Mountain front there remains a great level or shoulder, known to the westward as the Plateau region of the United States, to which this Raton Las Vegas plateau is analogous, if not a part.

For the region in northern New Mexico, lying east of the true Rocky Mountains and west of the Llano Estacado, approximately the region south of the Purgatoire and north of the Gallinas, I am obliged to use the above name in distinction from the surrounding country. This district embraces the buttes and mesas known as the Raton Mountains, Fishers Peak, the Mesa de Maya, and many other remnants of the former table-land, which mark the whole region, and in addition the plains of erosion upon which they stand. The cities of Trinidad, Folsom, and Las Vegas may be considered as marks along the northern, eastern, and western boundaries, respectively, while Raton Springer, Maxwell, and other points along the Santa Fe road between the Purgatoire at Trinidad and the Pecos are located upon it.

Its southern boundary is the superb Corazon escarpment of the Canadian Pecos Valley (see chapter on Red Beds), which runs eastward from the Pecos, at Pecos crossing to near the Texas line. This escarpment, as shown in the topographic maps, is over 1,800 feet in height.

The western border is the foothills, or "hog backs," of the eastern front of the Rockies. The northern border from Trinidad to Folsom is the north escarpment of the so-called Raton Mesa, which is followed by the Denver and Fort Worth Railway. The eastern border is less conspicuous, for it is the base-leveled shore line of the Llano Estacado formation.

This vast area stands out from the Rockies as a bench or shoulder above the level of the plains and surrounding erosion valley, extending some 200 miles to the east.

It is the remnant of a great plateau which existed around the southern end of the Rocky Mountains before the Llano Estacado (Miocene or Pliocene) epoch, the great mass of which has been degraded by the erosions of Tertiary and Quaternary time; the shore line of the old coastal plain now represented in the Llano Estacado having benched its present boundaries and removed much of its mass, which is deposited in the Llano Estacado formation. The later Quaternary erosion has still further degraded the plateau, and reduced its thickness and extent.

This region possesses a diversified surface aspect, consisting, however, of plains upon which stand great mesas of sedimentary rock sheets, often capped with lava, like Raton Mountain and Fishers Peak—remnants of the great erosion the region has undergone in Tertiary and Quaternary time. As a whole, however, it is a series of plains produced by degradation from one harder plain of stratification to another, from the Fishers Peak basaltic sheet to the Laramie sandstones, and from these to the flaggy limestone layers of the Colorado shales, as at Springer and Las Vegas, and from there down to the basal Dakota sandstones, where the latter are cut through, as in the Canadian Cañon, at the Corazon escarpment, the Red Bed floor is always reached.

The plateau or shoulder as a whole is a product, then, of the unequal

Simpson's Rest, Trinidad, Colorado.

Showing remnant of Raton Plateau from which lava sheet has been eroded.

erosion of the subhorizontal beds of the Upper Cretaceous from Laramie to the Dakota sandstones down to the Red Beds, inclusive, which are here included between the Red Bed floor and the Fishers Peak basalt. This erosion from top to bottom, via the successive plains of stratification, has partially removed more than 5,000 feet in thickness of sedimentary strata; and there is no evidence that the region has ever been submerged since Cretaceous time, either by the Llano Estacado shore line or the basins mentioned elsewhere. In fact it was the stream-worked land whose débris furnished much of the sedimentation for the rocks of the last-mentioned periods.

Concerning this region Prof. Newberry has said: "The vicinity of Raton Mountain has, in former times, been the theater of violent and wide spread volcanic action. At that time numerous mountain masses and subordinate buttes of traps were thrown up and floods of lava poured out, covering an extensive area in their vicinity. During this period of violence the Cretaceous rocks were locally much disturbed and metamorphosed, and the lowest members of that series elevated to, and perhaps far above, the surface of the ocean. At some time subsequent to the period of greatest volcanic activity, and yet apparently before the fires in the great furnaces were entirely extinguished, the Tertiary strata began to be deposited in the depressions and over the irregularities which then existed on the surface."

The structure of this shoulder is also unique, in that its strata incline towards the Rocky Mountains axis, and not away from it or against its own topographic slope, as can be seen at Trinidad and Las Vegas. (See profile.)

This structure, it will be seen, is inimical to favorable artesian conditions in most of the area, although the foundation of the whole region is the great water-bearing Dakota sandstones, and the testimony of the following drill holes bears out this proposition: At Trinidad an experimental well has been sunk over 2,000 feet, without reaching the sandstone or having a perceptible rise of water. Near Las Vegas, on the southern side, a similar depth was reached but no flow. At Springer, however, a slight flow at shallow depths was met, which is entirely due to local variations. These shallow wells may be possible in other places.

THE MALPAIS REGIONS OF NEW MEXICO.

The occurrence of intrusions such as impervious igneous rocks as dikes, lava flows, cinder cones, volcanic necks, etc., are frequent in New Mexico, the former being especially numerous in the Raton Las Vegas Plateau and in the mountains of west Texas, and the latter along the great fault between Austin and Del Rio. It is generally conceded that dikes are more or less fatal to artesian conditions, breaking the continuity of flow, and that craters' necks and other volcanic items are almost equally injurious to the prospects of water. By far the greater portion of the region east of the Pecos discussed in this paper, however, are free from them. (Figs. E and D, photos.)

Besides the igneous rocks of the mountain proper, large areas of the plains and basins of New Mexico and Mexico, but not in Texas, are covered by volcanic flows of lava and basalt hundreds of square miles in extent. In many cases these are accompanied by cinder cones or craters; in others they are fissure extrusions, and in others the source of the lava flows have not been determined.

Of these sheets there are two distinct types: First, those of more

recent age, which have neither been covered by subsequent sedimentation nor seriously degraded by erosion; secondly, more ancient and partially covered or eroded lava sheets of the plateaus.

The oldest class of these sheets are extrusions from the mountain strata, the extension of which towards the plain has been entirely degraded or which never reached them. In this older class are also true lava sheets or flows, which have been so much destroyed by erosion or buried beneath later sedimentation that only fragments of the original flows are now preserved or exposed. This class of eruptives occur in the great cap rock of the Raton Plateau.

The recent sheets are especially conspicuous in the vicinity of many of the ancient lakes' basins previously described; the proximity suggests that there is a close relation between them in age.

The Raton Las Vegas Plateau was originally capped by a vast sheet of basalt lava, which is still the determinative or initial point in the erosion plain of that vast region, but which has been mostly worn away. It still surmounts Fishers Peak, south of Trinidad, and the great Mesa de Maya, extending 50 miles east of there. It also caps the mesas and vast areas to the southward as far as Las Mora Creek. This malpais sheet or sheets must cover hundreds of square miles.

At a lower altitude and apparently of later age, along the eastern border of this ancient basaltic flow, at its contact with the Llano Estacado formation and in the vicinity of Folsom, there is a group of volcanic craters composed of cinder cones from 100 to 2,750 feet in height above the plain, from which have been extruded vast sheets of lava and basalt, covering the country for miles around and extending more or less irregularly from Folsom to Rabbit Ear Mountains, near the Texas line, and north and south of the road about 50 miles, partially covering an area of 1,000 square miles. The most conspicuous of these craters is Mount Capulin 6 miles south of Folsom station. This is a beautiful cinder cone, rising nearly 3,000 feet above the railroad, with a vast crater at its top nearly a mile in diameter, slightly broken down on its western side; from the summit of this can be seen many lava flows. To the southward from 6 to 20 miles are several similar craters, while to the northward are several smaller ones.

These are the most eastern known of the western United States region, and their occurrence at the contact of the great Llano Estacado shore lines and the Raton Plateau are interesting facts.

The cinder cones are clearly of a more recent origin than the adjacent basaltic cap of the Raton Plateau, for they are situated in an eroded valley, between the main mesa and an outlier, the Sierra Grande, (alt. 10,000), and at a lower altitude than either of them. They are also apparently more recent than the late Tertiary deposits of the Llano Estacado, the original surface of the lava resting upon the latter, and not covered by it except in case of the wind-blown débris.

These lava sheets are locally known as malpais. Most of these are vast areas of level rocky desert, absolutely void of economic value, except for grazing lands for sheep and goats, and should be considered as absolutely irreclaimable.

The Cimarron River, which rises in the vicinity of Folsom, has its source in springs from the Laramie sandstone beneath the Capulin and Huerfano lava flows.

The springs are as follows: South of town, one quarter mile northeast of the twin crater, there is a fine spring flowing from a pipe. Below the hotel there is a large spring in the cañon. Three miles below the town the Cimarron falls over lava beds. Two hundred yards be-

low these falls is the largest spring in all the valley, flowing a current 6 feet wide and 18 feet deep. One thousand acres are irrigated from this water. In Oak Cañon, north side of the mountains, there is another large garden irrigated by spring water. Much of this water is derived from the snowfall.

Leaving the Capulin crater, let us proceed southward along the margin of the great basins, and see other similar features. For 200 miles no more of these are encountered until we reach the head of the Franklin Hueco Basin, between the San Andreas and Gaudulupe Mountains, on the stage road from Socorro to Fort Stanton. Here, again, there is a great area of malpais lava, which is a terror to the traveler and barrier to the development of the country which it covers.

Since this chapter was begun Mr. Ralph S. Tarr has published* such a good description of this region that I quote here. He says, in substance:

> Fifty miles east of Rio Grande, between Carthage and Fort Stanton, is a flow of basalt bearing every evidence of being very recent. The point of extrusion is a small cone standing at the northern end. The flow is situated in a basin of interior drainage almost completely inclosed by mountains. The basin, which varies in width from 10 to 30 miles and has a north and south extension of fully 100 miles, is bounded by the Jicarilla Mountains on the east, the Hueco and El Paso on the south, and the Organs and San Andreas on the west. The area of flow exceeds 1,000 square miles. On the foothills of the mountains are quite distinct benches, which, with other evidence, prove this basin is the site of one of the Quaternary lakes, of which there are others in the vicinity.
>
> The loose gravels of the basin quickly absorb all the moisture which falls upon the surface, and the mountain torrents rarely escape far into the plain before being absorbed. A few newer brooks enter from the White Mountains on the northeast side, and they also sink into the soil a few miles from the outlet.
>
> The elevation at the northern end of this basin† is 5,360 feet, and at the southern 4,100.

The Dona Ana—Fort Selden flow.—The northern end of the floor of the Mesilla Valley is covered by another lava flow, through which the railroad cuts at Fort Selden. Pidocho Peak and several others, some 10 miles west of Messilla, are volcanic cones. Of these Dr. G. G. Shumard says:

> From the character and general appearance of these cones and lava streams I am disposed to ascribe their origin, to a comparatively recent geological period. They form part of an extensive volcanic chain, which may be traced north and south, for several hundred miles.

Continuing southward another region of craters, and flows occur south of the Southern Pacific, and west of El Paso about 30 miles. Here the conditions are similar to the others, the cones and lava flows being situated in the floor of the ancient basins.

The lava station sheet.—The northern end of the Jornado del Muerto Basin is also occupied by a great lava sheet 12 to 18 miles in area, or 96 square miles. This, too, is alleged to have come from a crater about 10 miles east of the railroad, and bears the same intimate relations to the basin floor as the other crater flows mentioned.

Another crater flow upon the floor of the basin is about 30 miles northwest of El Paso between Aften and Aden station, where there is an alleged cone of great magnitude, from which a narrow stream of lava flows southeastward about 20 miles.

There are other areas in New Mexico of volcanic lava, notably that south of Grand Station on the Atlantic and Pacific Railway.

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*A Recent Lava Flow in New Mexico, by Ralph S. Tarr, Am. Naturalist, 1891.

†This basin is the head of the El Paso or Franklin Hueco basin described on a previous page.

In Trans Pecos, Texas, no true lava flows or craters have been described, although many igneous sheets occur in the mountains. Prof. Von Streeruwitz says in his report on this region that:

> Volcanic rocks are represented by lava, compact and cavernous, basalt, basaltic wacke, obsidian, retinite, and trachytic rocks in the Quitman, Sierra Carrizo, Eagle, Van Horn, and Davis, Viejo, and Chinatti Mountains, and probably at least as dikes in the Guadaloupe, Franklin and the mountain ranges not yet examined.

The relation of the cinder cones and subrecent flows to those of northwestern New Mexico and Arizona, I can not state from personal observation, but there is no doubt that there are some common features between them.

Proceeding southeastward into Mexico they still continue and in cases exhibit evidence of activity, increasing southward toward the neck of Mexico, where the present epoch seems to be but a southern continuation of the volcanic and lacustral conditions, which so recently prevailed over the basin region.

The fact that these cinder cones and lava flows occur in the floor of the Quaternary lake basins, or as in the case of Capulin area, upon the edge Llano Estacado deposits, is indicative of their recent origin, and future investigations will show an intimate connection between the drying up of the basins, and the activity of these volcanoes, although some of our ablest geologists do not believe in this relation.

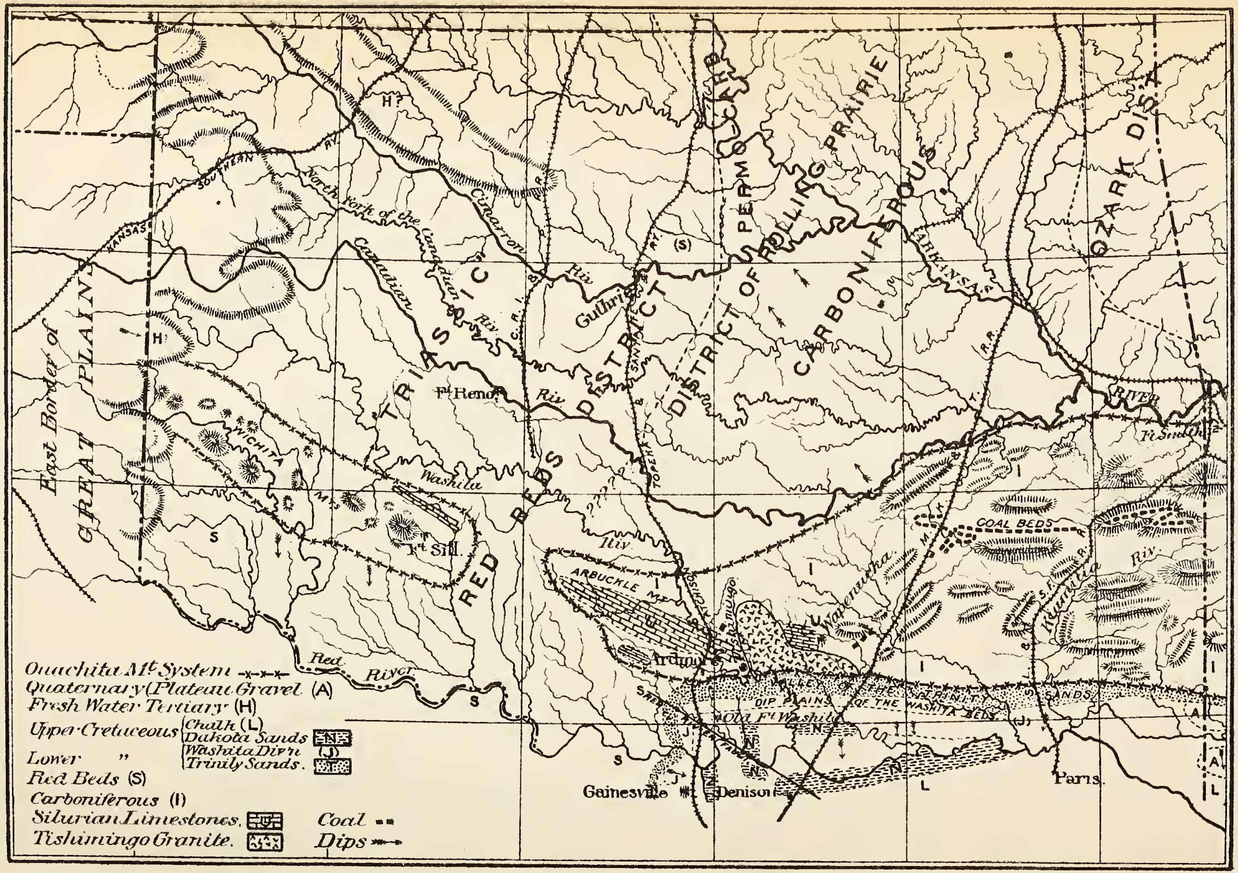
It is also evident from the investigations that eruptive activities have occurred in the Texas, New Mexican region, from Cretaceous to present time, and at least three well-defined epochs, are at present recognizable, which may serve as an aid for future observations, to wit:

1. The Austin Del Rio system of Shumard Knobs, ancient volcanic necks or laccolites bordering the Rio Grande embayment begun in Cretaceous time, and the lava sheets of which have been obliterated by erosion.

2. The lava flows of the Raton system, which are fissure eruptions of Tertiary time, and which are only partially removed by erosion.

3. The cinder cones and lava flows of the Capulin system, late Pleistocene time, which still maintain their original shape and extent.

Water conditions of the Malpais region.—Igneous rocks possess small capacity for imbibition and transmission of water except through means of joints and fissures between them and these are very few. Even when cellular or scoriaceous there is usually no free connection between the cavities, and hence the honeycombed feature is of little value. In fact they are characteristic of aridity, and in themselves are of little value as water-bearing factors except where they may protect from evaporation some underlying saturated porous sheet, which condition exists in many places throughout the Raton Las Vegas Plateau and at Folsom, where the Malpais rests on porous sandstone from which occasional springs issue. In general they are not favorable to artesian development.


East Border of
GREAT PLAINS
TRIASSIC
RED BEDS
DISTRICT
DISTRICT OF ROLLING PRAIRIE
PERMO-CARB
CARBONIFEROUS
OZARK DIST
Cimarron
Riv
North Fork of the Canadian Riv
Canadian
Riv
Washita
Riv
Red
River
ARKANSAS
RIVER
Ft Smith
Guthrie
Ft Reno
Ft Sill
WICHITA MTS
ARBUCKLE MT
Ardmore
Tishomingo
Wapanucka
Kiamitia
Riv
COAL BEDS
VALLEY OF THE TRINITY SANDS
DIP PLAINS OF THE WASHITA BEDS
Old Ft Washita
Gainesville
Denison
Paris
SOUTHERN
KANSAS
RY.
C. R. I. & P. R.R.
SANTA FE
TOPEKA
ATCHISON
M. K. & T. R.R.
S. F. R.R.
Ouachita Mt System
Quaternary (Plateau Gravel (A)
Fresh Water Tertiary (H)
Upper Cretaceous
Chalk (L)
Dakota Sands
Washita Divn (J)
Trinity Sands.
Lower "
Red Beds (S)
Carboniferous (I)
Silurian Limestones.
Tishimingo Granite.
Coal
Dips

X.

WATER CONDITIONS OF OKLAHOMA AND INDIAN TERRITORY.

The Indian Territory, including Oklahoma, may be provisionally divided into three parallel east and west belts, each containing a marked diversity of geologic structure and corresponding topographic expression.

The northern or Cherokee-Oklahoma belt includes the country north of the Canadian; the greater part is prairie with spots of timber, decreasing in density toward the west. This belt may be subdivided into three districts: The eastern or Cherokee, the middle or Oklahoma, the western or Arapaho. The Cherokee division, with the exception of a small area of Ozark hills in the northeast corner, is mostly composed of carboniferous rocks, with an undulating topography similar to that of southeast Kansas, and lying wholly within the humid region. The Oklahoma section is a typical Red Bed region in its western half, with undulating prairies and soft disintegrating structure. It is well watered by streams and surface wells. The Arapahoe division is the ragged eastern border of the great plains country, with its charateristic fresh water deposits of sands and grits occupying the flat divides, as recently described in the adjacent west Kansas region by Prof. Robert Hay.* And in the accompanying chapter on the Llano Estacado:

Concerning the Indian Territory I have recently published the following description: †

These plains are the newest or culminating formation in western Texas, Kansas, and Indian Territory; they are now slowly receding westward because of the head water erosion of the streams that indent this eastern border, and in this manner the underlying structure and topography are revealed. The northern belt of Indian Territory distinctly belongs to the Kansas division of the United States.

The middle or mountainous belt lies south of the Canadian Arkansas River. A mountain system traverses it from east to west and marks the great barrier between the upper Mississippi Valley and the Texas-Arkansas regions of the United States.

The third and southern belt, the description of which must be left to a future paper, includes the region between the mountainous belt and Red River. It is the northern termination of the Texas region of the United States. It includes many topographic and geologic features which are the result of neozoic sedimentation against the southern border of the mountains.

THE MOUNTAIN REGION OF CENTRAL INDIAN TERRITORY.

With the exception of the Ozark hills in the extreme northeastern corner, the mountains of Indian Territory are the direct westward continuation of the Ouachita system of mountains which has been described ‡ as the mountainous area between Hot Springs, Ark., and the Staked Plains of Texas, including the various points known as the Poteau, Seven Devils, San Bois, Shawnees, Jacks Fork, Black Fork, Winding Stair, Sugar Loaf, § Cavenal, Stringtown Hills, Limestone Ridge, Potato Hills, Arbuckles, Wichitas, Navajoes, and other mountains. These mountains are south of the Arkansas-Canadian drainage and must not be confused with the Ozarks of southwestern Missouri. Dr. J. C. Branner's coming report will doubtless give us needed light on this relation.

The mountain belt has three distinct subdivisions: (1) An eastern, or Arkansas; (2) a central, or Chickasaw; (3) a western or Wichita. Its areal extent may be compared to an arch whose apex is southward, as marked by the course of the Canadian, Arkansas, and Red River drainage; its eastern member in Arkansas and the Choctaw nation is a forest area of vertically folded Carboniferous shales and sandstones resembling the Appalachian country; the western member in the Chickasaw and Co-

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* See Bulletin 57, U. S. Geological Survey.

† See notes on a reconnoissance of the Ouachita Mountains of Indian Territory. American Journal of Science, August, 1891.

‡ Arkansas Geological Survey, 1888, Vol. 2: The Geology of Southwestern Arkansas, by Robert T. Hill.

§ Near Fort Smith; not the Cretaceous butte of the same name east of Caddo.

manche nations is a mostly treeless region, and consists of low folds of hard white and blue Silurian limestones and eruptives; the keystone or central Chickasaw region consists of an area of granite and Silurian limestones north of Tishomingo.

The most marked feature of these mountains is the excessive compressed and vertical folding which the whole region has undergone, and the displacement of these folds by a lateral dislocation which has squeezed them into S-shaped flexures. So excessive is this folding that every stratum in the mountain region south of the coal fields can be said literally to be standing upon its edge as shown in the figures. This system of folding is complicated and the writer has not had time for minute study necessary to interpret it. In general, two great trends or strikes are conspicuous. The first and oldest is about 25 degrees south of west; this is frequently dislocated by an apparently later movement resulting in northeast and southwest trends, all of which are accompanied by overlapping and lack of continuity. The direction of the folds has a marked effect on the political features of the region, all lines of transportation and public highways practically following the valleys of erosion in the trend of the folds.

The coal fields, for which the name Fort Smith-McAllister area is most appropriate, are of great commercial importance, for they are the chief source of fuel supply for the Arkansas-Texas area. These extend along the northern border of the mountains and are terminated on the southwest by the Silurian and granite field of the Tishomingo district, which are an apparent barrier between this and the Texas-Ardmore coal field.

The Arbuckle Mountains constitute a great and wonderful development of the Silurian system, although this has not been hitherto appreciated, and afford a superb example of folded structure. This folding is beautifully shown in the valley of the Washita, which has cut a deep and tortuous water gap through these mountains, where, unobscured by forest growth, fold after fold of the stratified limestones and shales appear in startling boldness. Several journeys through this gap only increased the appreciation of the greatness of the task of thoroughly delineating the section, the complexity of which may be inferred from the accompanying figures.

West of Duncan the limestone hills are buried beneath the red beds for 20 miles, but again appear in the neighborhood of Fort Sill, forming a low ridge north of and parallel to the Wichita Mountains, as is explained later.

Section across Indian Territory from south to north along Atchison, Topeka and Santa Fe Railway.—The accompanying north and south section and profile from Gainsville, Tex., to Guthrie, Okla., gives at least an idea of the sequence and foldings of the Arbuckle region. Proceeding southward along the line of the Atchison, Topeka and Santa Fe, the typical gypsiferous red beds of Texas, Kansas, Indian Territory, and New Mexico—the alleged Triassic—are see from Guthrie to Oklahoma City, lying in a disturbed but comparatively subhorizontal position, showing greater dips than the Cretaceous, but none of the complicated folding of the Paleozoic strata. South of the Canadian the Carboniferous clays and sandstones appear with the excessive dips of the Ouachita folds. At Buckhorn Creek, east of Dougherty, the coal-bearing beds of the Carboniferous are seen dipping north at an angle of 65° and involved in the folds of the adjacent limestone hills. In this vicinity there are terranes at the base of the Carboniferous, the age of which I could not determine, especially a great thickness of soft sandstone, but the succeeding limestones are undoubtedly a part of the Silurian system.

Proceeding southward from Dougherty to Berwin the limestones, shales, and sandstones of the Precarboniferous succeed each other, but so complicated is the vertical folding that the writer must confess his utter inability to determine their proper succession, even after considerable study. These rocks occupy in cross section almost invariably a subperpendicular position for a distance of 12 miles. From north to south, however, the following distinct subdivisions are apparents.

Continuing southward along our section the mountains cease coincident with the limestones, and after a mile of black shales (No. 7) the well defined Carboniferous sands and shales begin near Berwyn and continue for 29 miles along the railroad to the vicinity of Overbrook. These all occur in vertical folds, apparently coincident with or at least a part of the same system to which the Silurian limestones belong, but which, owing to their disintegrating character, have been leveled down to a low undulating plain. Ten miles south of Ardmore the Trinity sands, the base of the Comanche series, rest unconformably against the Carboniferous (the Red Beds being absent), and upon these in turn to the southward the subhorizontal beds of the Lower Cretaceous.

A parallel north and south section 20 miles west of the Santa Fe road shows the presence of the Red Beds and the absence of the Cretaceous, the latter having deflected southward through Texas.

It is not alone in the mountains of the Paleozoic areas, however, that this remarkable vertical structure is seen, but much of the Carboniferous prairie regions east of the Red Beds are based upon it. For 20 miles north from the Red Bird to the Arbuckle Mountains the undulating prairies, void of any high relief whatever, except

FIG. 12.

SECTION OF INDIAN TERRITORY SHOWING RELATIONS OF STRATA TO ARTESIAN WELLS.

The mountain rocks are too vertical to be of value, while the gently inclined plains present ideal conditions for securing artesian wells north of Red River, the receiving area being the sands outcropping in the valley of stratification at *a*. Water beds: Dakota sands, *e*; Trinity, *a*.

slight rises where the sandstones prevail, are based upon the almost vertical Carboniferous shales and sands, as shown in our diagrams.

The Wichita Division.—The Arbuckle folds west of Duncan are buried beneath the Red Beds for some 30 miles, but outcrop again some 8 miles north of Fort Sill, marking the northern margin of the Wichita Mountains, forming a low foothill which is comparatively inconspicuous, owing to the overshadowing height and sharpness of the adjacent eruptives of the Wichita Mountains proper.

These mountains rise abruptly above the level of the Red Bed prairies, which surround them on every side, and their sharp, jagged outlines present striking and exquisite scenery. The ragged peaks of igneous rock present a strong contrast to the stratified ridges of the eastern and central divisions of the system. Although in Arkansas the latter have a similar elevation above the surrounding plain, they have not the rugged peaks and points of the Wichitas, and are covered by forests. Their aspect is Appalachian; the arid Wichitas remind us of the Rockies; the eastern Ouachitas are the eroded remnants of stratified rocks with their characteristic topography; the Wichitas consist of igneous rocks, hard, firm, ragged, and barren.

These mountains extend westward from Fort Sill 120 miles to the one-hundredth meridian and were partially mapped out by Marcy and McClelland years ago,* and T. B. Comstock has recently made an interesting reconnoissance of them.† The most prominent of the many peaks are Mount Scott and Mount Sheridan; the former is 2,004 feet above sea level, 1,200 feet above Fort Sill on the plain below, and 1,700 feet above Red River, 50 miles distant. Though neither high nor extensive, the Wichitas are models of topography and mountain structure. Mount Scott is a solid mass of red feldspathic granite with little quartz, while neighboring mountains are composed of green stones, basalts, etc., indicating two widely different types of igneous rocks.

The westward continuation of these mountains is buried beneath the Tertiary sediments of the Staked Plains and with it the history of the relation of the Ouachita system to the Rocky Mountains. At one or two places in No Mans Land and north of Clarendon, Tex., I am told that erosion has cut down to the rocks of this mountain system, but I have not been able to find the localities.

The composition of the Wichitas is unlike that of any mountain area of the southwest, and, so far as I could see, presents no structural resemblance either to the basin-surrounded mountains of the Trans-Pecos or the early Paleozoic buttes and denuded folds of the central Texas region. Their age is not determined. They are certainly Post-Silurian and the Red Beds have in part participated in the movements, but the eruptives may be Post-Cretaceous, or even later. The apparent absence of the Lower and Upper Cretaceous in the composition of the Wichitas is especially noticeable. Their trend and composition plainly place them in the Ouachita system.

The country in general is well watered with streams and springs, and nearly everywhere that experiments have been made surface wells have been obtained. I have heard of only one artesian well experiment, and this was at Fort Reno, but no results had been secured at the time of my visit, a year ago.

The topographic conditions favorable for artesian possibilities are found in the high river divides forming the western end of the Ardmore-Wichita mountain system, which crosses the southern third of the Territory, and the high drainage divide of the Cimarron and South Canadian rivers, which is from 200 to 350 feet higher than those streams, and along the crest of which flows the North Canadian, which could be easily diverted down either slope for irrigating purposes.

These two divides or ridges form elevated receiving areas, which, other conditions being favorable, would afford a bountiful artesian supply in the lower valleys of the Cimarron, the South Canadian, the Washita, and Red rivers. The stratigraphic conditions are more difficult to determine, however, owing to the unconsolidated nature of the strata, but as far as ascertained they were favorable as seen in profile, north and south across the State.

Except the Wichita-Arbuckle mountainous axis, forming the divide of the Red and Washita drainage, the rocks are nearly all composed of sands and clays of Red Beds. Whether they present a favorable alter-

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*See Exploration of Red River of Louisiana, Marcy.

†See First (Second) Annual Report of the Texas State Geological Survey, Austin, 1889.

nation of porosity and imperviousness for the transmission of the surface rainfall beneath the valleys of the streams mentioned, however, can not be positively stated.

Between the ninety-seventh and one hundredth meridians there are very favorable conditions for securing artesian water in these valleys, and the experiment should be tried at Guthrie, Kingfisher, Minco, Anardarbo and Henrietta, Texas, where there is a possibility of obtaining artesian water from a purer source beneath the saline and gypsum beds, and where extensive irrigation could be conducted should water be obtained.

The Valley of Upper Red River.—The valley of Red River north of Henrietta and perhaps a portion of the adjacent uplands in Clay, Wichita, Wilbarger, and Hardeman counties, which lie in a synclinial valley, are some 400 feet lower in altitude than the receiving strata of the sloping plains which begins at the Wichita Mountains to the north and some 200 feet lower than the axis of Carboniferous hills to south, present an interesting field for artesian investigation and present favorable conditions, provided the prevalent Red beds formation is sufficiently pervious for the transmission of water.

The Dakota sands in Indian Territory.—No more ideal conditions for magnificent but as yet undeveloped artesian supply could exist than those presented by the Dakota sands in the southern edge of Red River Valley in the Chickasaw Nation east of Washita River.

The Dakota or Lower Cross Timber sands outcrop in the highest divide between the Red River and Washita, and incline at the rate of 100 feet per mile towards Red River. The sands occur as a narrow belt (3 miles wide) of timbered land beginning at the Washita River and running due east to the Blue and from the Blue to the Boggy. This ribbon is about 3 miles south of old Fort Washita and 30 miles north of Denison, from which city it can be seen as the highest visible land in Indian Territory. North of the sands is the narrow parallel strip of Washita prairie, (here known as the 7-mile prairie). South of the timber is the sandy clay, dip plane prairie, underlaid by the Eagle Ford shales, known as the Carriage Point prairie. The inclination of the strata and topography here are such that in my mind, although a drill has never been sunk, abundant artesian water can be obtained from the Dakota sands in Red River Valley, anywhere due north of and opposite Grayson County, Tex., and south of the Territory Cross Timbers at a comparatively shallow depth and if driven deeper, a better supply from the Trinity (Paluxy) sands.

A discussion of the limestone springs of the Arbuckle Mountains will also be found in the chapter entitled Water Conditions of the Hard Limestone Regions.

THE WATERS OF THE HARD LIMESTONE REGION.

The underground streams of limestone regions often attain large proportions, and flow many thousand gallons of water, such as the streams of Nickajack and Mammoth Cave, Ky.

But these streams are the collected underground drainage representing in their volume the water of immense area, and if the reader will only consider the relative area occupied by stream water to that occupied by rock, as shown in caverns, he will see that the chances of the artesian drill from above would be very small for striking this stream, and if struck that there is absolutely no pressure to cause it to rise.

Perhaps the most remarkable and abundant supply of water in the

arid region, however, is that found in the eastern slope of the Guadalupe Mountains of southern New Mexico and the Davis Mountains of Texas, and which drains into the Pecos River, affording the chief water supply for the magnificent irrigation development of the Pecos Valley.

This region has been little reconnoitered scientifically and the outlines of the mountain system not even delineated, and with the exception of a valuable report by Dr. G. G. Shumard nothing has been published concerning it.

The Guadalupe mountain area occupies about one thousand square miles in southern New Mexico and adjacent Texas, west of the Pecos and between the thirty-second and thirty-fourth degrees of latitude.

It is made up mostly of hard blue soluble limestone of Permian and earlier Paleozoic rocks, accompanied by some eruptives and granites and sedimentary rocks of later age may be present.

The limestones which compose its greater mass, however, are jointed, thinly stratified, and slightly inclined, affording every opportunity for the collection and transmission of the rainfall which the area receives. In addition, the central peaks and axes are snow covered for a greater portion of the year. Overlying the limestone and at its contact with the Red beds which surround the base of the system, there is an immense stratum of coarse loosely cemented conglomerate composed of the débris of the limestone which forms a magnificent medium for retarded transmission of water. Resulting from these conditions of structure are innumerable springs and streams of superb volume. The whole of the brief time allotted to study the vast region embraced within this report could have been profitably spent in the Guadalupe region alone, but only a short time was allowable for its study. In view of the conditions, however, the writer would advise artesian experimentation in the Tertiary formations surrounding the Guadalupes at lower altitudes than the mountain rocks located relative to it, such as Toyah, Pecos, and Roswell and where the water is apt to be stored by underground reception from contact with the underlying limestone. The volume of these streams according to measurement of Col. Nettleton is given in his report and they constitute the chief volume of the Pecos River, that stream not receiving hardly a drop of water between them and its mouth 400 miles distant.

In addition to the streams there are numerous springs of great volume, which rise through the Red beds and in the river, along the eastern margin of the mountain area, such as shown in the river near Eddy, and at the Chisholm ranch and other points near Roswell.

This superb volume of underground water has created an impression that at most points in the Pecos Valley east of these mountains artesian water can be obtained, but the writer must confess that the truth or falsity of this hypothesis can only be determined by further experimentation. That the later formations of the valley plains surrounding the mountains receive a great deal of this water which does not reach the surface by springs is very evident, and as seen in the wells at Roswell, Toyah, and Pecos City, all of which are just without mountainous area, but not one of which has penetrated to the mountain rock or Red beds. So far as I have been able to ascertain the Pope experimental well, sunk in 1858 about 8 miles east of the Pecos, reached the mountain structure and proved waterless, confirming the theoretical conclusions that massive limestones are not reliable artesian media.

The disposition of the immense amount of water pouring down the cavernous limestones can not all be superficial, however, but much of

it must find its way into the overlying clays and gypsums of the Red beds. The Pecos River flows near the contact of the newer formations and the mountain rocks of the Guadalupe (see map) where the river has cut down to the limestone, as at Eddy, N. Mex., the springs burst out of the limestone immediately at the river. Where the Red beds overlying the limestone as between Seven Rivers and Roswell the springs appear as "Johnny holes," *i. e.*, sink holes which sometimes overflow in large streams, as at Chisholm ranche, or may merely fill the "crater," as they are called.

There can be no doubt that these lake springs have their source in the water of the underlying limestones which forces its way up through the gypsum and produces sink holes just as they are produced in hard limestone regions.

These holes are among the most interesting phenomena of New Mexico, occurring as they do in the midst of the Red bed prairies away from water courses and in the most unexpected places.

They are often of great diameter and filled with beautiful water, often of a dark or greenish color and overflowing their lowest edge into a beautiful stream which runs off a few yards or miles to the Pecos River. Large farms are irrigated from these streams, for the particulars of which the reader is referred to Col. Nettleton's report. They occur only in the valley of the Pecos, in New Mexico and Texas. The principal ones are as follows, as given by Mr. Roessler:

As indicated on the blanks, I could give you no idea of number and extent of springs nor the flow of water from them in the space there allotted.

I will first mention artesian wells. Many have been contemplated, and but one has been attempted, and that of Mr. L. M. Long, work on which has been suspended on account of accident to machinery.

Take the rivers and springs in rotation as they are important in magnitude:

Rio Pecos.—As you know, this river traverses ranges 25 and 26 east, north of the second correction line, and also south of that line for a distance of about 20 miles, when the bend runs into range 27 east occasionally, but the principal portion of the river is embraced in range 26, as far south as township 19 south, when it bears east and traverses ranges 26, 27, 28, and near line of Texas, 29 east.

Rio Hindo.—This river is formed by the confluence of Rio Bonoto and Rio Ruidoso, in township 11 south, range 18 east, and running east confines itself to townships 10 and 11, and discharges into Rio Pecos.

North Spring River.—This stream rises in section 36, township 10 south, of range 23 east, from monstrous springs. Twenty yards from the head this stream is fully 40 feet wide and averages that for a distance of about 4 miles running eastwardly, where it empties into the Rio Hondo, in section 34, township 10, range 24 east. There are two slight falls in the course of this river. It runs smoothly, without any rush. The water is limestone, with an almost imperceptible tinge of gypsum. It is clear and limpid, with a depth of 2 to 4 feet. No watershed, and it has never varied (rising or falling) 1 inch within the memory of the oldest citizens. There are no rocks of importance at its head or along its banks. The volume of water is increased along its route or along its banks. The volume of water is increased along its route by several valuable springs.

South Spring River.—This river rises in section 22, township 11 south, of range 24 east. The description of North Spring River will apply to South Spring River, except that it is deeper, not so broad, the water runs much swifter, clear, same class of water, no rocks, carries about the same volume, no important rise or fall, is about 5 miles long, runs north of east, and empties into the Rio Hondo in section 9, township 11, range 25, 700 yards from the Rio Pecos.

Middle Bernando River.—This river rises in section 5, township 10 south, range 24 east, from springs. It is about one-half the size of North Spring River, runs more rapidly, same class of water, few rocks, very seldom rises, always full supply, forms confluence with the North Bernando Spring in section 14, and South Bernando River in section 22, township 10, range 24, empties into Rio Hondo in section 25, township 10, range 24.

North Bernando River.—This spring is in section 11, township 10, range 24. It supplies water to irrigate two good farms and swells the Middle Bernando River in section 14. Length of stream about 500 yards.

South Bernando Spring.—Rises in section 17, township 10, range 24 east, from

springs. Carries nearly as much water as the North Bernando; same class. Description of latter named will describe this. The above three Bernandos deposit their waters in the Rio Hondo.

Bitter Creek and Springs.—This creek comes from a lake in section 9, township 10 south, of range 25 east. This lake is fed from subterranean sources. The valley abounds in springs, and they feed this creek along its source. There is another (nameless) creek which runs into the Rio Pecos a (distance of about 400 yards) in section 15. This (Bitter) creek is about 3 miles long and empties into the Rio Pecos in section 28, township 10 south, 25 range east. Water strongly alkali. Sufficient water for a half dozen farms; three in operation.

Seven-Mile Spring.—This is 7 miles south of the mouth of Rio Hondo. A continuation of very free springs, capable of supplying water for three or four farms. It rises in section 13, township 12 south, of range 25 east, and runs into the Rio Pecos in section 20, township 12 south, of range 25 east. Empties into Rio Pecos in section 33, township 12 south, range 26 east. Splendid water; no rocks.

Nine-Mile Spring.—Nine miles south of Rio Hondo. Rises in section 31, township 12 south, of range 26. Empties into Rio Pecos, in section 33, township 12 south, range 26 east. Facsimile of Seven-Mile Spring.

Rio Feliz.—This stream empties into Rio Pecos in section 35, township 13, range 26. It rises in the mountains more than 50 miles west of the Pecos, runs a fine stream of water for 4 or 5 miles, sinks and rises again a considerable stream within 3 or 4 miles of the Pecos. Fine waters, 25 feet broad (in pools), 3 miles from Pecos. Subject to sudden freshets from its head.

Rio Penasco.—Rises in the mountains 68 miles west of the Pecos, runs 8 miles, sinks, rises again in section 18, township 18, south of range 26 east. Plenty of water at head; size and class of South Spring River. However, acequias have been taken out at the sinks, and it is said that cattle have trodden it down so that water runs some 30 miles in old bed. The land is being rapidly located.

I have taken you down the Rio Pecos some 50 miles, and have left out many springs and living lakes. I could go on to Seven Rivers, Rocky Arroyo, Black River, Delaware River, Grape Springs, and various minor streams, springs, and lakes. The water sinks in several of them, but often rises again. One branch of Seven Rivers runs under a mountain and disappears. The banks of the Rio Pecos are studded with excellent springs. One spring (although on both sides of the Pecos) yields more water than the supply of the city of Denver.

South of the Texas-New Mexican border the basin formation again approaches the mountains, and the Pecos River flows over it for a distance of about 75 miles. The water from the mountain rocks is probably imbibed when it reaches this softer and more unconsolidated formation, and is tapped by artesian wells at Pecos City and Toyah.

A third and remarkable illustration of the occurrence of the water in the massive limestones of the arid regions is found in northern New Mexico, near the Villa de Musquez de Santa Rosa, where magnificent springs of great volume flow from the limestone foothills of the Sierra de Santa Rosa. These springs furnish the beautiful body of water which flows down the Rio de Sabinas and afford a sufficient quantity for irrigation to support an agricultural population of 50,000 people in a region which would otherwise be a total desert.

It is an interesting fact to note that these hard limestones of the Sierra de Santa Rosa are simply the metamorphosed chalks of the Texas region (Comanche series).

The limestone springs of this formation in the Indian Territory, while not attaining the size of those of other regions mentioned are nevertheless numerous and abundant, furnishing a large volume of water which drains off southward into the Red River, that stream having hardly a tributary on its south side worthy of mention east of the Wichita, the drainage from almost its very banks flowing southward into the Trinity. The main limestone springs of the Indian Territory are near Fort Sill, at Cache Creek, near Old Fort Arbuckle, at Woodford and around Wild House, Caddo, and the Washita.

The limestone springs of central Texas.—In the counties of Lampasas and San Saba erosion of the Colorado San Saba and Llano drainage has cut through the chalky and softer Comanche strata to the hard

limestones of the Carboniferous and Silurian strata from which magnificent springs flow in great volume. These springs, especially those at Lampasas, are among the lowest and most beautiful natural phenomena in our country and worthy of every traveler's attention.

They burst out of the limestone fissures in such volume that large streams flow from them, which are utilized for extensive water power. They are well described in Mr. Roessler's statistical paper.*

In conclusion, I need only say that in the foregoing pages I have only outlined for the Southwest the underlying principles of the water question as known to-day. Many details have been necessarily omitted, and many of the areas discussed have been only partially reconnoitered, and with the exception of the eastern part none thoroughly explored.

The question of the application of this water to irrigation is left entirely to the irrigation engineers, and to the special agent in charge of the reports, of whom most valuable practical information may be obtained.

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* Letter from the Secretary of Agriculture, transmitting a report on the preliminary investigation to determine the proper location of artesian wells within the area of the ninety-seventh meridian and east of the foothills of the Rocky Mountains, August 21, 1890; R. J. Hinton, special agent in charge. Senate Ex. Doc. No. 222, Fifty-first Congress, first session; Report of F. E. Roesler, C. E. division, field agent for Texas, pp. 243–319.

ON THE UNDERFLOW AND SHEET WATERS, IRRIGABLE LANDS, AND GEOLOGICAL STRUCTURE OF NEBRASKA, WITH ITS EFFECT UPON THE WATER SUPPLY,

BY

L. E. HICKS,

Assistant Geologist for Nebraska.

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I. IRRIGATION IN NEBRASKA.

1. GEOLOGICAL STRUCTURE OF THE STATE AND ITS EFFECTS UPON THE WATER SUPPLY.

The problem of irrigation and water supply has everywhere a most intimate relation to the underlying rocks, but nowhere is this relation closer than in Nebraska. Of the three principal series of rocks, Permo-Carboniferous, Cretaceous, and Tertiary, the first, occupying a relatively small area in southeastern Nebraska, has little influence in determining the water supply available for irrigation. Next to this comes the Cretaceous, occupying nearly one-third of the surface, and in the western part of the State the Tertiary, occupying nearly two-thirds of the surface. The Permo-Carboniferous and Cretaceous are the bed rocks of the region which they occupy, and are overlaid with gravels, sands, clays, and loess of the Quaternary age. The Tertiary beds, however, are not covered by any later deposits, but form the surface of the country in the region occupied by them, and also form the subsoil to a very great depth. The distribution of these formations is shown upon the accompanying map, Fig. 1.

The two formations which dominate the circulation of moisture, both on the surface and beneath it, are the Cretaceous and the Tertiary. Their control of the water supply depends upon the form of the strata and the texture of the component rocks. The form is that of a synclinal basin whose western rim is 3,000 feet higher than the eastern. (See Fig. 2.) Stratigraphically the Permo-Carboniferous rocks form the floor of this tilted syncline; but physically, and with reference to the water supply of the western two-thirds of Nebraska, where alone the problem of irrigation is seriously considered at present, it is the Cretaceous which forms the impervious floor of this broad basin. The permo-Carboniferous may be ignored in this discussion, since it occupies a small area outside of the arid belt. The upper member of the Cretaceous is a shale which is almost perfectly impervious or water-tight. Upon this compact floor is laid down a series of porous Tertiary rocks, grits, conglomerates, gravels, sands, vesicular limestones, and marls, which fill the basin and form the surface of the country, with its general eastward slope of about 10 feet per mile. The Tertiary rocks absorb water like a sponge, and their position upon a floor of compact Cretaceous shales, together with the eastward slope of the country insures the return of this moisture to the surface in the form of springs and artesian wells.

Artesian wells may be developed wherever a local change of texture in some Tertiary stratum renders it impervious over a sufficient area, so as to form a roof over the water-bearing stratum. This, however, is quite exceptional. As a rule the Tertiary beds are all porous; consequently the underground waters appear as innumerable springs, usually too weak to be of great value separately for irrigation, though some of them are very strong, and the combined effect of the small springs in the streams which they feed becomes an important factor.


NEBRASKA
KNOX
BROWN
ROCK
HOLT
CHERRY
ANTELOPE
PIERCE
GRANT
HOOKER
THOMAS
BLAINE
LOUP
GARFIELD
WHEELER
MADISON
BOONE
ARTHUR
McPHERSON
LOGAN
VALLEY
GREELEY
PLATTE
CUSTER
NANCE
KEITH
SHERMAN
HOWARD
MERRICK
POLK
LINCOLN
PERKINS
DAWSON
BUFFALO
HALL
HAMILTON
YORK
CURVE OF ANNUAL PRECIPITATION
IN THE LOUP VALLEY
Jan. Feb. Mar. Apr. May Jun. Jul. Aug Sep Oct Nov Dec.
INCHES ,93 43 142 281 309 320 500 266 166 101 64 89
REFERENCE
Bottom Lands
Marshes
Lakes
Rolling Prairie
Timber
Ridges
Sand Hills
Water Shed
DRAINAGE MAP
OF THE
LOUP VALLEY
Showing the Drained and Undrained, Areas, Table Lands, Lagoons, Silted-Up Valleys, Sand Hills and the Bluffs Bounding the Valleys and Forming the Edges of the Table Lands.
By L. E. Hicks, Ph, D. F. G.S.A.
Asst. Geologist U.S. Dept. of Agriculture

In my report for 1890 the location of many of these springs was indicated on the map, but they have been found to be so numerous along almost all principal and tributary streams that such notation becomes impracticable. Passing along a river in a boat one may observe that hardly a rod of either bank is free from seepages, forming rills and pools above the level of the current. The gauging of a stream at different points, no tributary intervening, will often show a much greater volume at the lower point due to the accessions from springs.

In the Loup Valley increase of volume holds good in almost every instance. The streams become larger as one follows them downward independently of the influx of tributaries. In other parts of the Great Plains, however, not infrequently the result is precisely opposite; that is, the volume of a stream will be less instead of greater at the lower point. This also depends upon the geological conditions. Not only the structure of the terranes, but also the previous history upon which that structure depends, must be brought into view, in order to explain this anomaly of a weakening in volume, and even disappearing altogether.

The fact is that the rivers of Nebraska are flowing in valleys which were cut by older rivers, generally with a depth and breadth far greater than the present valley. These old valleys, some of them steep and sharp as well as deep, were silted up during the Pliocene submergence, which was the latest phase of the Tertiary age. This submergence or drowning of the rivers and valleys in a great inland lake, and the emergence which restored them to the light of open day, are very recent events, so recent that the present rivers have not had time to restore their valleys to the former depth by washing out the sands, clays, and gravels deposited there. Given sufficient time and these rivers will master the silt and carry it away in suspension as fine mud, or push it and roll it along the bottom to a new resting place nearer the sea, if it is too large and heavy to be carried by the waters. But at present the silt often masters the river. There is so much of it that the water, preyed upon also by evaporation in the hot and thirsty air of the plains, is all dissipated, spread abroad in wide sand washes, and lost to view in the depths of the old silted-up valleys. It requires a very strong volume of water to maintain a perennial current in such a silt-gorged valley. Even the regal strength of the North Platte is insufficient for these arduous conditions. Coming out of the mountains with a flow of over 10,000 cubic feet per second, it is often wholly swallowed up in its own sands between North Platte and Columbus. The same thing happens to the Republican River in certain parts of its course. Many of the smaller streams entirely disappear after a course of a few miles, never reappearing.

THE UNDERFLOW.

The streams thus becoming entangled in the silt of their own valleys are indeed lost to view, but they are not really lost. They go to feed the underflow. No physical feature of the Great Plains is more impressive, when once fully realized, than the fact that a mighty invisible river accompanies each visible one. The underflow is vastly broader and deeper than the visible river, and it is always there, while the river in sight may cease to flow. The only point in which the river excels is velocity. The percolation of water through silt is very slow as compared with channel velocities, and this limits the volume which may be developed by subflow ditches or pumping. Where the silt is very porous, by reason of its coarseness or the form of its particles, and at the same time the water is under considerable pressure, the

velocity of percolation may approach that of free-flowing streams. In some places in the valley of the Platte so copious is the underflow that when it is tapped at the distance of several miles from the channel it responds to powerful pumps almost as freely as if the supply were drawn from a subterranean lake.*

SHEET WATERS.

The spongy mass of Tertiary rocks lying upon the impervious Cretaceous shales is by no means homogeneous in texture or uniform in thickness. It varies in thickness from 1,000 feet to a mere skin cover a few feet thick, lying over and concealing projecting knobs left by erosion on the surface of the old Cretaceous land. At such points it is useless to search for sheet water. The character of the rocks clearly indicates that the drill has penetrated the dry and barren Cretaceous shales. A little attention to the geology of the region will save the repetition of expensive failures in such localities.

The variation in texture runs from clays and tolerably compact marls to coarse gravels and conglomerates. At some level, varying from the subsoil to some hundreds of feet, a natural water table is formed, at and beneath which all the rocks are saturated and the more porous beds yield supplies to the wells. Frequently several distinct veins of sheet water are found, the deeper veins having the greatest volume and pressure. Were it not for the cutting out of these water-bearing strata by the valleys each of them would be a source of flowing wells. As it is, the sheet waters are invaluable as feeders of the wells. The general seepage of the porous Tertiary beds, where they are not interstratified with compact layers so as to form distinct veins of sheet water, is the source of the innumerable weak springs along the rivers. The stronger springs occur where porous beds carrying sheet waters are cut by the erosion of the valleys.

Thus in the general circulation of moisture a neat balance is maintained. If in some valleys the surface streams enter the earth and become invisible, merged in the underflow, in others the invisible subterranean waters burst out in springs to feed the surface streams.

The controlling feature of the water supply of western and central Nebraska is the presence of a great mass of porous materials, forming the surface and filling the old valleys, beneath which lies a compact floor of impervious rocks. Thus the waters are absorbed, hidden, drawn away from the surface out of sight, but not lost. Except by evaporation, which is the great waster of land moisture, and which is especially active upon the wind-swept and sun-parched treeless belt, the waste of moisture is reduced to the minimum. It is true there are not many rivers, at least not in the western counties. The very conditions which tend to conserve the moisture—rapid absorption and occlusion by porous beds—tend at the same time to minimize the surface drainage. It is not deficient rainfall so much as peculiar geological conditions which make the rivers few in number. The land is newly won from the waters and drainage lines are as yet imperfectly established. Old channels are silted up and new ones have not been cut out. A porous and uneven surface drinks up the waters that fall from the heavens; consequently surface streams are few, but the underflow and sheet waters are copious.

Such conditions prevail widely in western and central Nebraska, but have their typical illustration in the Loup Valley, the peculiar features of which are discussed at length in the body of this report. In one

* See p. 187 for further data on the rapidity of percolation.

point, however, the Loup Valley is exceptional. It has not only copious underflow and sheet waters bursting out in beautiful springs, but also numerous rivers. It is a well-watered country.

2. THE IRRIGABLE LANDS OF NEBRASKA.

The irrigable lands of Nebraska are the valley lands. This is accurate as a general statement, although two classes of exceptions may be noted. In the first place a limited area of the table lands may be irrigated by pumping from wells, or by utilizing flowing wells wherever these may be developed. In the second place some of the lower tablelands may be reached by ditches. The best opportunities for high-line ditches occur in the valley of the Republican River and along the main Platte below the confluence of the South and North Platte.

For the most part, however, the waters of Nebraska rivers will be absorbed in the irrigation of the lands lying within the main bluffs bounding their valleys. It is not only the bottom lands which can be easily supplied, but the second and third bottoms or benches. When these are included in the reckoning, there is more than enough good land in the valleys to absorb the whole visible supply of water. It would be bad economy to carry the water at great expense away from the valley lands which need it, and upon which it can be carried at minimum cost. It is true that some of the valley lands are the poorest in the country, sandy and alkaline. This is because the rivers of the plains seldom overflow their banks. The silt or river mud which enriches the bottom lands in other regions is not deposited in these valleys to cover and fertilize their sterile sands, and the soil in low spots becomes alkaline also, because it lacks the washing and sweetening effects of floods. The proper remedy, both for alkali spots and sterile sands in the valleys is artificial flooding. The fields should be diked and kept covered with water in the nongrowing seasons, thus dissolving and washing out the alkalies and covering the sands with fertilizing mud for the next crop. By such methods we may not only irrigate the good valley lands, but first redeem and then irrigate the poor valley lands.

THE PLATTE VALLEY.

The largest body of irrigable land in Nebraska lies along the Platte River. No accurate survey has been made showing the exact amount of irrigable land in this broad and beautiful valley. Indeed no such survey has been made or attempted for any part of Nebraska, except the Loup Valley, the results of which are embodied in the present report. In the absence of such survey and of the exact data which it would have furnished, we may estimate the average breadth of the Platte Valley, not including the channel, at 5½ miles. Its length west of the ninety-eighth meridian, including both valleys above the confluence of the South and North Platte, is 441 miles. This gives over one and a half million acres in a single great valley, an amount which is much beyond the capacity of the Platte to irrigate unless we count upon a very high duty of water. Due consideration being given to the infrequency of irrigations required during each growing season in a region of considerable rainfall, it is not improbable that with careful management the greater part of this fine body of valley land might be supplied. We can not safely estimate more than 6,000 cubic feet per second as the average normal volume of the Platte, and not more than 4,000 cubic feet per second in critical seasons. Prof. Hay and myself

found the North Platte at Camp Clarke, on the 29th day of May, 1891, to be flowing at the rate of 8,075 cubic feet per second. On the 24th day of June, 1891, I found flowing in the Platte, near Columbus, Nebr., above the mouth of the Loup, 18,240 cubic feet per second. Both of these measurements are above the normal volume, and the latter very much above. The Platte actually goes dry some two months almost every year at the very point where I found it sweeping along like a moving sea. If we should reckon upon 6,000 second feet as the normal volume, it would still require the very high duty of 250 acres to the second foot in order to irrigate the Platte Valley with its own waters.

Below the town of North Platte, which is situated at the confluence of the two rivers, the bluffs are not so high as to prevent the table-lands being reached by gravity ditches from the Platte. The old ditch at Kearney is proof of what may be accomplished in this line, and a new company is now organized for the purpose of putting in a high-line ditch to water the table-land north of the Platte, between the Platte and Wood rivers. The south side presents even greater facilities for irrigating the table lands.

On the North Platte River the bluffs are too high (600 feet by aneroid barometer) and rugged to be economically surmounted. At the same time the fine body of irrigable land in the valley makes the attempt unnecessary. The valley lands are being rapidly supplied, ditch construction being more active here than in any other part of the State.

On the South Platte, in Nebraska, little can be done in the way of irrigation because the water is absorbed by appropriators in Colorado. The underflow is the only resource, but the attempts to utilize that have not been very successful. The South Platte has, however, a small tributary in Nebraska, Lodge Pole Creek, which has a unique and important place in relation to irrigation. From it the oldest irrigating ditch in the State was taken to furnish water to the garrison and gardens of Fort Sidney. This pioneer ditch is still in successful operation. Many other short ditches are furnishing water to the fine meadows and plow lands below Sidney, so that this little valley of Lodge Pole Creek has, by its enterprise and activity in irrigation, set a noble example for other communities to follow.

THE REPUBLICAN VALLEY.

As regards the acreage of irrigable lands in the valley of the Republican River, the same relation to the water supply holds good as in the case of the Platte, viz, the valley lands exceed the united irrigating capacity of the chief river and all its tributaries. These valley lands are more uniformly good than in the western valleys as a rule. Moreover the fine table lands adjoining the valley are low enough to be reached at moderate cost. Hence the acreage of good land which may enter into competition for the water of the Republican River is almost unlimited. It is purely a question of priority of appropriation as to what lands shall secure a portion of the precious liquid, since there is not enough for all. The people seem to realize this in some measure, and accordingly numerous irrigation enterprises have been projected, several of which are now being vigorously pushed forward towards completion.

THE NIOBRARA VALLEY.

The Niobrara is a considerable river, but its physical peculiarities rob it of much of the importance in respect to irrigation which it might

otherwise possess. From the 102d meridian eastward it flows in a cañon, broad enough, it is true, to inclose some good irrigable land, but not enough to utilize all the water of the river. The bluffs are too high and rugged to permit the irrigation of the adjacent table-lands.

West of the one hundred and second meridian its valley is broad and moderately shallow, bounded by grassy slopes, but here the stream is small.* Nevertheless its steep gradient ($12\frac{1}{3}$ feet per mile), rapid current, pure water, and the fine body of irrigable land along its upper course, give it considerable importance. No ditches have yet been taken out from it.

THE WHITE RIVER VALLEY.

The White River and its tributaries, together with the copious springs which are so numerous in that region, are capable of irrigating a considerable body of land, and their waters have already been appropriated to a considerable extent. The land is of good quality and easily reached by short ditches.

II. SURVEY OF THE LOUP VALLEY.

Acting under the instruction of the chief geologist, Prof. Robert Hay, I have made a careful survey of the central region of the State, watered by the Loup River and its tributaries. The Loup was selected as a typical river of the plains. Its head waters and its entire course lie in the plains, and it exhibits in the highest degree those strongly marked peculiarities which characterize the drainage of the treeless belt. This valley also deserves special attention because it lies in the debatable zone, the subhumid, where the question is forever recurring "to irrigate, or not to irrigate;" where the rainfall is copious enough to encourage the farmer to plant and, in most seasons, fills the land with plenty, but sometimes fails at the critical moment.

EXTENT AND SURFACE FEATURES.

It is difficult to fix upon precise boundaries for the Loup Valley. On the south and east the watershed is well defined, but on the north and west the drainage merges gradually into an undrained region of sand hills and lagoons where it is impossible to draw an exact boundary line. Guided by the best practicable approximation, however, we set down the extent in latitude and longitude as follows: From longitude 97° 17′ (west of Greenwich) to 102° W.; and from latitude 40° 50′ N. to 42° 28′ N., or nearly five degrees of longitude and two of latitude. Its area is 13,428 square miles, or 8,593,920 acres, *one-eighth of which is irrigable land.*

The surface features of the Loup Valley are of great interest, as being excellent types of certain topographic forms, and also of considerable

* On the 4th of September, 1887, I measured it in range 51, west of the sixth principal meridian, in the southern part of Dawes County, and found it there to be 21 feet broad, 2 feet deep, and flowing at the rate of $2\frac{1}{3}$ feet per second. It discharges, therefore, 98 cubic feet of water in each second of time. This measurement was taken on its upper course, and in one of the driest months of a dry year. (Bulletin No. 1, Ag. Exp. Sta. of Nebr., entitled "Irrigation in Nebraska," by L. E. Hicks, p. 5.)

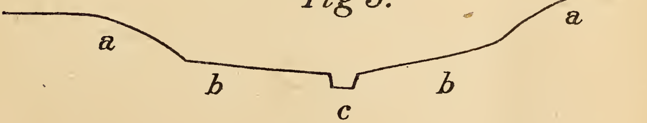
practical importance in their bearing upon the water supply. In describing these surface features it is necessary to designate in a general way two divisions of the Loup region, an upper and a lower region. The general facies of these divisions is quite unlike, although they have no exact boundary, but blend together and inosculate in the most intricate manner. Along the valleys the characteristic features of the Lower Loup run far up the country, while on the other hand those of the Upper Loup region run far down along the divides between the rivers.

In the Lower Loup region, along the main Loup, and along the lower courses of its large tributaries, we have the normal types of land sculpture belonging to a region of somewhat advanced erosion. The broad valleys, with their first and second bottoms well defined, are flanked by grassy hills of gentle slope and moderate height. Journeying across the country between the rivers, one finds a complete mesh of drainage lines, some of them dry ravines, others carrying perennial streams, but collectively covering the whole surface with an elaborate system of open drainage. There are no closed basins. The streams have been at work long enough to cut an outlet for every depression, to invade every acre of the primitive terrane, and to mellow down the declivities to graceful curves. Occasionally a sharp cut, like the "Crazy Man's Leap" at Fullerton, for example, shows that active erosion is still in progress. But the general aspect is that of somewhat advanced land sculpture, the water having already reduced the general level of the table-land, and dissected it into swelling hills and open valleys, with intricate windings of ravines, which have lost their early cañon-like sharpness. In all this Lower Loup region the topographic elements of structure are essentially but two in number, dissected table-lands, and valleys, all well drained and highly fertile.

Higher up along the rivers the same two elements still appear, but additional elements come in, and the hills and valleys belong to a different type. The hills are higher and steeper. Sharp cuts, steep walls bare of vegetation, frequent cañons, rugged and picturesque with their deeply gashed walls fringed with cedars, all show that the erosion is in its first vigorous stages. In places where the primitive terrane was composed largely of sandy strata, its dissected remnants will be sand hills, or at least, sandy hills. However this kind of sand hill produced by water sculpture dissecting a sand-bedded terrane into hills, is very different from the typical wind-drift sand hill. Fine examples of dissected sand hills may be seen south of Broken Bow in Custer County.

The valleys of the Upper Loup region are also quite different from those farther east. The elements of the cross section are reduced in number. An Upper Loup Valley usually has the following cross section:

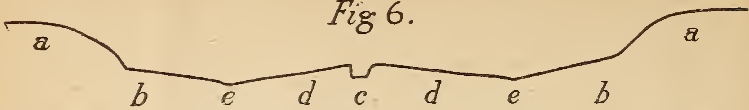
Fig 5.



a Bluffs. b Hillslope. c Channel.

A Lower Loup Valley has usually the following cross section:

Fig 6.



a Bluffs. b Hill slope: c Channel. d Floodplain. e Depression, frequently marked by swampy or "gumbo" soil.

Figure 6 is the normal cross section of the lower or middle course of a mature river valley. The hill slope (b) is a strip of alluvial land, often quite narrow, running along the foot of the bluffs, and composed of the wash from them. It slopes towards the channel. The flood plain (d) is built up of river silt, and slopes away from the channel because this silt accumulates faster in the slack water nearest the central line of silt movement. The depression (e) is the meeting point of these two opposite slopes where the minimum of deposition occurs, because of its remoteness from the channel on the one hand and from the bluffs, another source of detritus, on the other hand. The occurrence of swamps here is natural because the ground is low; and the fine impervious clays which constitute "gumbo," and which are deposited there because at that distance from the channel the current is too sluggish to carry any other kind of silt to the spot, promote the same result by preventing the percolation of water through the subsoil.

Figure 3 is a unique type of valley structure, which is best exemplified in the region of the Great Plains east of the Rocky Mountains. Instead of the numerous elements of the normal type shown in figure 4, and which would appear still more numerous if the second and third bottoms or terraces were introduced in the figure as they often actually occur in nature, only three elements remain, viz, bluffs, hill slope, and channel. It is as if the middle of figure 4 had been cut clean out. The reason why there is no flood plain is that there are no floods; and the reason why there are no floods is that the physical conditions of the whole region combine to prevent floods by rapid absorption of the rainfall into the earth, whence it finds its way slowly by subterranean courses to the streams instead of flowing off quickly upon the surface. All this will appear more clearly when we have traversed the whole series of physical conditions in the Loup Valley, which we shall proceed to do.

This peculiar type of valley is not merely a matter of curious inquiry for the student of earth forms, but has a practical bearing. Such valleys have no bottom lands in any proper sense of the word, because they have no flood plain. Sometimes the nearly level stretches of the slope b, formed by the wash from the hills, closely resemble bottom lands. But in all such valleys the good arable land is very liable to be interspersed with sterile, wind-drifted sands and alkali patches. Neither of these belong to a normal flood plain. The sands, if they existed at any time, would be cut down and covered over with fertile mud and the alkalies would be washed out.

At the headwaters of each stream in the Loup region still another phase of valley structure appears. A series of wide basins, walled in by sand hills and joined by narrow valleys, form natural meadows where enormous crops of hay are harvested annually. These are thoroughly saturated with moisture, except in the driest seasons, and, indeed, pass insensibly into swamps, bogs, ponds, and lakes. Here are the perennial sources of the rivers, though not until the traveler passes some miles down the valley does he observe any well-defined channel or perceptible current.

The most significant surface feature of the Upper Loup region is yet to be described. It is the entire absence of surface streams, or even their dry channels, from large areas. Of the whole Loup region 4,700 square miles (35 per cent) is undrained. This undrained area is occupied by three types of earth-forms, all of them not only of great scientific interest, but also of great importance in their effect upon the water supply. These are lagoons, sand hills, and silt-engorged valleys of an old drainage system, now unoccupied by any stream.

The lagoons were first described by the author in a paper read before the Geological Society of America at the Indianapolis meeting, and published in their bulletin, vol. 2, 1890, p. 25, from which I quote the following paragraphs and illustration, including also statements respecting the old, now dry, valleys of this region, which will suffice on that head for the present:

In regions of advanced erosion the watershed is a line. On this side the raindrop falling may run off to the Atlantic; on that side its twin drop falling may run off to the Pacific. On the plains the water parting, instead of being a line, bulges out here and there into a broad band. It splits into two lines and loops around a space which does not belong to the valley on either side. Here falls a drop which runs off to the south; yonder, a score of miles away, falls a drop which runs off to the north. Between lies a broad table-land, where the rain may sink into the earth, and by subterranean ways ultimately get into some river, or it may be evaporated and return to the heavens; but the one thing which rain persistently does everywhere else—that is to say, run along the surface in ravine, creek, river, to the ocean at length—that one thing it persistently refuses to do on these table-lands.

Some notion of the peculiarities of surface which cause this unusual behavior of the waters may be obtained from the stereogram presented herewith, illustrating a portion of the surface in the western part of Custer County, Nebr. A sort of regular or persistent irregularity is apparent. In contrast with the ordinary landscape there is a striking absence of *leading lines*. There are valleys, but they lead nowhere; there are basins, but they have no outlet; there are ridges and hills, but they have no continuity and no definite arrangement. Every depression soon bumps up against a hill; every hill slopes off into a hole.

The general level is well maintained over a considerable area. The higher points are so equal, so numerous, and so close together that they form a level sky-line when viewed from a little distance; but from these summits down to the bottoms of the "lagoons" may be 50 or 75 feet. The roads, following section lines, cross hills and valleys in endless succession. In other regions one may make the distinction of traveling "across the country" or not, according as he follows the valleys or takes them transversely. Here there is no choice; it is "across the country," no matter what direction is taken.

All of the elements of composition are curves. The horizontal planes and sharp angles of water sculpture are conspicuously absent. The hills are low domes, the basins have the same form inverted. There may, indeed, be a level space at the bottom, but that is a secondary modification. The sloping sides of the lagoons are grass covered and wash but little, yet enough is carried down to make notable accumulations when reinforced by the remains of a luxuriant vegetation induced by the rich soil and abundant moisture. As much as 20 feet of soil has been observed in some of these lagoons.

Here we see the natural reservoirs for the storm waters of the plains. In some of them water remains throughout the year; in almost all it is easily reached by digging. A cistern is often dug in the bottom of a lagoon, and being covered to prevent evaporation, it preserves the collected storm waters for household use. Still more frequently a supply for animals is obtained by simply deepening the basin with plow and scraper. The economic value of these natural storage basins has brought them

into general notice, and accounts for the fact that they have a popular name. This name, "lagoon," is closely restricted to the depressions on the rolling surface of the high, grass-covered table-lands. I have never heard it applied to the numerous closed basins among the sand hills or the "kettle holes" of the drift.

Lagoons occur over a wide region east of the Rocky Mountains, where the rivers have not invaded and modified the old lake bottom. They are more numerous in Custer County, Nebr., than in any other locality which has come under my observation. Here there may be a score of them to the square mile. In other parts of the Great Plains they are few and widely separated. They vary from 1 acre to 50 acres in area.

Are there no outlets whatever for the surface flow of water from these depressions? There may be, but the moment that occurs the type is destroyed. The outlet deepens to a ravine, the ravine to a cañon, the cañon opens into a valley, and so on to the sea; the primitive surface of construction has been captured and converted into a surface of erosion. This process is constantly active. The chisel of water-sculpture is forever hacking away at the remnants of the table-lands. Their edges are gashed with fresh ravines, and here and there a cañon pierces the very heart of the plateau.

But the resistance to the encroachments of water-sculpture is considerable, and the manner of resistance is obvious. So long as the lagoons are not filled to the brim there is no chance for any "wash" to get a start. Should there be a great increase of the rainfall, so that precipitation should exceed evaporation, the lagoons would fill up and overflow, and the table-lands would rapidly melt away. Their preservation is therefore good evidence of constancy in climatic conditions during the whole period since this lake bottom became dry. At least it is conclusive evidence that there has been no great variation in the direction of increased rainfall, though there may have been greater aridity. These curious structural forms constitute a sort of weather record which runs far back into the past. It was dry enough when Lake Cheyenne was spilled out of its bed by upheaval to evaporate the remnants of that lake in the lagoons, and it has since been dry enough to keep them from filling and overflowing. They even give us a glimpse of the climate which prevailed in a period far more remote, as we shall see when we inquire into their origin.

To this question of the origin of the lagoons the most queer and contradictory answers, ranging all the way from wallowing buffaloes to spouting volcanoes, may be elicited from the old settlers. The generic relations of the lagoon type are clear enough. It is a structural form unmodified by erosion. But among structural forms is this an example of the sedimentary, the igneous, the coralline, the glacial, or the eolian type, or is it a combination of some of these? The title of this paper implies that it is sedimentary. But sedimentation tends to produce horizontal planes. If there are exceptions, such as torrential cones and sloping beaches, they have obviously no application to the case in hand. Yet the materials displaying this structural form are indubitably lake sediments—Tertiary marls. Their unique form must, therefore, have been influenced by forms of surface already in existence when this region became a lake. None of the familiar accidents of upheaval, tilting, or folding, or faulting to which horizontal sediments are subject will account for such forms as these. Igneous action produces lofty cones, craters, geyser basins, dikes, bosses, laccolites, and sheets of extruded lava which may present considerable irregularities of surface. Some of these igneous forms of construction, if they were mantled over with a sheet of lake sediment, might give a result something like the lagoons and rounded hills of the table-lands of Custer County, but there is no reason to suspect that any sort of igneous agency has been concerned in the matter. The hint contained in the identity of the popular name lagoon with that which designates a prominent type of coralline structure is only misleading. The promiscuously irregular forms of the glacial drift are more promising. Hillocks, kettle holes, and morainal lakes might possibly assume a facies not unlike the forms in question, at least with the help of a thin cover of fine sediment; but the region is clearly beyond the recognized limits of glaciation, and no drift is found either on the surface or beneath it.

We come, then, by the method of exclusion to the eolian type of construction, and we soon find that, apart from the objections lying against other hypotheses, the suggestion that we have here an example of the influence of a preëxisting surface shaped by the action of the wind has much to commend it. The materials of wind construction are drift-sand and dust. The letter does not produce topographic forms of much magnitude, and in this discussion, at any rate, may be disregarded. Drift sand is, however, an element of construction which produces important topographic results upon the Great Plains at the present time, and it has probably been as busy in previous geologic cycles as it is now.

The fundamental type of a single sand hill is a half cone lying upon the flat-side, its base concave, facing the prevailing wind and forming a "blow-out," and its elongated apex stretching off to leeward. A succession of these overlapping upon each other gives a serrated ridge running parallel with the prevailing wind. Shift-

ing winds give cross-ridges which shut in sections of the troughs lying between the ridges first formed and produce closed basins. In a region of newly formed sand hills the ridge-and-trough structure parallel with the direction of prevailing winds is distinctly visible, but where the sands have been long tossed about by shifting winds the leading lines are obscured, the ridges are cut through by fresh blow-outs, and these may be found facing in all directions.

Such a surface mantled over with lake sediments would present the same forms which we see upon the table-lands. The sharpness of the serrations would be mellowed down to graceful curves, the closed basins would form the lagoons, and the whole surface would present gentle and irregular undulations, reminding one of chopping waves, after the violence of the storm has passed, arrested and fixed in mid-ocean. The well sections show much sand beneath the surface marl of these table-lands, and, upon the whole, there is good reason to believe that this interesing topographic type is the combined result of eolian and sedimentary processes. The character of the climate during the last period of emergence preceding the lake period may therefore be inferred to have been similar to that now prevailing in the same region. The hypothesis of preëxisting sand hills is only intended to apply to regions of constantly recurring and closely packed lagoons, such as we find in the western part of Custer county. The isolated depressions of other regions may be due to some of the numerous accidents which produce lakes and ponds.

It may be objected to this hypothesis that in the progressing subsidence which produced the Tertiary lake the sand hills would be leveled down by wave action on the shore. This result would certainly follow the progressive encroachments of a lake which had already attained considerable dimensions, but in the first stages of its formation in the center of the depressed area wave action would be very slight; the waters would quietly rise above the sand hills, leaving them and the closed basins between them undisturbed, except that slight rounding off and softening of their sharper features which, being still further mellowed down by a light covering of lake marl, produces the gentle undulations which characterize the table lands. Custer county is, if not in the very center of the old Lake Cheyenne at the time of its greatest expansion, at least well removed from its shore line.

We have also other distinct evidences that the encroaching lake did not level all before it. Old valleys of erosion, obscured indeed but not concealed by the newer sediments, stretch for miles across the table-lands where now no stream flows. It is true that these would be more difficult to obliterate than the sand hills, but their preservation is nevertheless significant. Whatever weight they may have as evidence of the gentle advances of the lake waters over the rough, wind-tossed, and water-sculptured surface of the plains, they possess an interest of their own as evidence of a long period of emergence before the last submergence. The rivers had time enough to cover the surface with their lines of erosion even more completely than the surface is covered at the present time. The channels now occupied by rivers show, here and there, marks of preëxisting channels, and those which are still unoccupied remain over to the credit of the older drainage system.

All this series of events falls within Tertiary time. The older drainage system of which I have spoken wrought upon Tertiary beds, and the erosion thus produced makes the later Tertiary unconformable with the earlier. We have here the evidence of cycles of emergence and submergence, of arid and humid epochs, of wind-swept plains and ancient rivers, of structural forms invaded by agents of erosion and again reconstructed—all within the limits of Tertiary history. In order to ravel completely the tangled threads of this history it would be necessary to pass in review the events accompanying the upheaval of the Rocky Mountains, perhaps also the physical history of regions more remote. That does not, however, belong to this discussion. I have merely aimed to decipher the geological record so far as to discover a probable cause for the peculiar structural forms which have escaped destruction simply by reason of their peculiarities. I have reached the conclusion that they are the results of sedimentation upon a surface previously shaped by the action of the winds. In other words, the lagoon type is a combination of the sedimentary and eolian types of construction.

The characteristic features of hills composed of wind-drifted sands are too familiar to require extended description. The surface is persistently irregular, uneven, and destitute of leading lines, such as are established by drainage. Unevenness of surface and porous texture are both developed in the highest degree, thus insuring the complete and almost instantaneous absorption of the rainfall and the entire absence of surface drainage.

These sands are quite different from pure silica in their power to retain moisture. Instead of being composed of pure silica they have a large

proportion of feldspar, mica, augite, and other complex silicates in their composition. They are earthy and argillaceous rather than clean quartz sands. They absorb moisture rapidly and in large quantities and retain it a long time, yielding it upwards little by little to growing plants and evaporation, and downwards to form the sheet waters which feed the wells, springs, and rivers.

It is obvious that the peculiar topography and surface texture of the underdrained area must profoundly affect the hydrographic and meteorological phenomena of the whole region. The sand hills are vast reservoirs of moisture. From them, and still more from the saturated meadows, bogs, marshes, ponds, lakes, and lagoons, evaporation is active and incessant, producing frequent local precipitations and increasing the volume of rainfall during storms of general distribution. The underflow and sheet waters must of necessity be copious in an area of considerable precipitation and no surface drainage. But the geological structure beneath the surface is no less potent in its influence upon subterranean waters than the form and texture of the surface, and hence this topic will come up again after the geological structure has been described.

Before leaving the subject of surface features, or topography, of the Loup region, it is proper to say a word about the gradients of the Loup rivers and their levels relatively to each other and to the Platte River. These gradients may be exhibited in tabular form as follows, that of the Platte, which is abnormally high for so large a river, being added for comparison:

	Feet per mile.
Platte	7.1
Main Loup	5.46
Middle Loup	7.3
North Loup	6.1
Beaver Creek	8
Cedar Creek	7.6
West Beaver Creek	9.6

It will be observed that the main Loup has a lower gradient than the Platte. In this respect, as in some others, it behaves more like a mature large river than the parent stream. Its large and constant volume in contrast with the Platte, which sometimes goes dry, has no doubt a causal relation to its relatively low gradient.

As regards the practical bearing of these gradients upon irrigation, all of these rivers have fall enough to facilitate the construction of ditches. Slope enough may be given to a ditch to secure a good flow of water and yet gain rapidly in height above the river, so that second and third bottoms, lying considerably above the channel, may be watered from ditches of moderate length.

From the fact that the relative gradient of the Platte is higher than that of the main Loup, while they run nearly parallel for 75 miles, it follows that, starting from their confluence, where they are on the same level, at each point above the Platte will be flowing at a higher level than the Loup, the amount of difference increasing as we ascend. Irrigation of the lands lying between the Platte and the Loup can therefore be accomplished most easily from the Platte. At some points it would not require a very deep canal to turn the Platte bodily into the Loup.

Another interesting point in the relative levels of the rivers is coördinate with that just named. It is that each Loup river or considerable tributary, taking them in succession from the southwest to the northeast, is flowing at a lower level than the preceding one. This is

admirably shown in the general cross section kindly furnished by Col. E. S. Nettleton from a survey made by Mr. W. W. Follett, which is appended to this report.

GEOLOGICAL STRUCTURE OF THE LOUP VALLEY.

The following diagrammatic section (Fig. 6), running the length of the Loup Valley in a general northwest-southeast direction, illustrates the geological structure:

Broadly speaking, the structure is the same as that of the whole State, as described above, viz, a synclinal basin filled with porous Tertiary rocks and floored with impervious Cretaceous rocks, the whole series having a tilt to the southeast. The Tertiary beds vary from 25 to 500 feet in depth or thickness. In them the Loup and its tributaries have excavated their valleys to the depth of from 100 feet to 300 feet. The main Loup flows over the depressed southeastern lip of the basin and catches the whole volume of underflow and sheet waters. Its channel from Fullerton to Genoa is cut to a slight depth into the impervious bed rock of Cretaceous shales. Near Genoa it enters the old, silt-engorged valley of the Platte and unites with that stream 20 miles lower down.

Here then we have an admirable adjustment of natural conditions all tending to conserve and equalize the flow of water. Upon an uneven and porous surface, much of it wholly destitute of drainage lines, the falling rain is received. Much of it sinks beyond the reach of evaporation, and its further movement underground is facilitated by the great depth of porous beds streaked with the gravels of buried rivers and lake beaches. Not being able to descend indefinitely, because it encounters the impervious bed rocks, it moves laterally, supplies the sheet waters for the wells, bursts out in springs along the valleys, feeds the underflow of the rivers, and finally is all gathered up in the channel of the Lower Loup by reason of the fact that this is cut down into the impervious floor of the basin. This is the chief cause of the large and remarkably constant volume of the Loup. It is even more potent than the amount and distribution of the rainfall. The latter supplies the moisture; the geological conditions conserve the moisture and economize and equalize its flow. As it frequently happens that habits of economy are of greater importance for acquiring wealth than the amount of one's income, so it may be in the natural world. The amount of the rainfall may be secondary in importance compared with the physical conditions which determine its dissipation in the air, or its absorption and conservation in the soil. Still the amount of the rainfall, and its distribution through the year, are fundamentally important and deserve the next place.

THE RAINFALL OF THE LOUP VALLEY, ITS DRAINAGE, AND SEASONAL DISTRIBUTION.

The Loup Valley has been regarded as having a rainfall sufficient for agriculture without irrigation. This opinion was uniformly entertained by its inhabitants from the time of its first settlement until last year (1890), when the prevailing and severe drought shook the confidence of many who had been firm believers in the sufficiency of the rainfall. There is, indeed, a tradition of irrigation having been prac-

ticed by the Mormon settlement at Genoa many years ago, and the remains of ditches are exhibited as old irrigation ditches. But they are no doubt the boundaries of fields, since they have neither the grade nor alignment of irrigation work. Instead of a record of primitive irrigation we have here a relic of the trench-and-bank system of inclosing fields—a method very natural in a region scantily supplied with timber. Hence it appears that irrigation has never been applied in the Loup Valley, and there is not now, to my knowledge, an acre of irrigated land in the whole region. It was not even thought of till last year, and the schemes which originated there have already lapsed into oblivion on account of the unparalleled precipitation of the present year,* and the magnificent crops, produced without irrigation, which are now being harvested. But the popular belief does not settle the question. At least irrigation may be extremely advantageous, greatly increasing the yield in ordinary years, and furnishing the only sure reliance in critical years, even if it is not an absolute necessity. It is still worth while to note the facts and record the possibilities of artificial irrigation in a region so well watered by nature. It is a settled conviction of the writer, unshaken by the remarkable experience of the present year, that irrigation is not only entirely practicable in this rich valley, but that it will be highly advantageous, a source of large profits to individuals, and a means of largely augmenting the agricultural importance this of region.

The rainfall is 23.74 inches. This is a goodly amount, and yet not of itself sufficient to justify wholly the popular faith. The total annual precipitation hovers rather near the danger line. But when we consider the seasonal distribution of this moisture the case looks more hopeful. There is a distinct, well-marked division of the year into a rainy season and a dry season, and the former comes just when the crops need the moisture, the latter just when the least harm will result from a deficiency. The rainy season extends from April to September, inclusive, and the dry season from October to March. In the six months, April, May, June, July, August, September, the precipitation is 18.42 inches, or 77½ per cent of that for the whole year. In the six months, October, November, December, January, February, March, the precipitation is only 5.32 inches, or 22½ per cent of that for the whole year. The detailed data upon which these general statements are based appear in the following

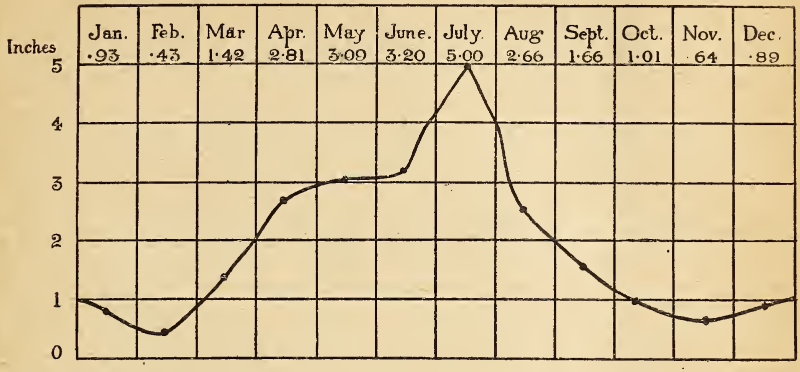
Table of precipitation, by months.

Rainy season.	Inches.	Dry season.	Inches.
April	2.81	October	1.01
May	3.09	November	0.64
June	3.20	December	0.89
July	5.00	January	0.93
August	2.66	February	0.43
September	1.66	March	1.42
Total	18.42	Total	5.32

* The summer of 1891.

The same facts are graphically exhibited in the following

Curve of annual precipitation in the Loup Valley.



This table and diagram were constructed from the rain-gauge records of five stations in the Loup Valley, the observations covering periods of one to fourteen years. The position of each station, the period covered by the observations, and the mean result for that period, are shown in the following

Table of weather stations.

Name.	County.	Latitude north.	Longitude west.	Period.	Mean.
		° ′	° ′	*Years.*	
Genoa	Nance	41 26	97 43	14	27.19
West Hill	Platte	41 33	97 49	5	20.58
Palmer	Merrick	41 14	98 15	1	21.70
Ravenna	Buffalo	41 2	98 54	3	26.54
Sargent	Custer	41 38	99 22	6	22.69
Mean of five stations					23.74

All these meteorological data are collated from the Weather Reports of Prof. G. D. Sweezy, published in the annual reports of the Nebraska State board of agriculture. The rainfall of the present year is not included. Its abnormal volume may be inferred from there ports for the month of June, which are as follows:

Table of rainfall at nine stations in the Loup Valley for the month of June, 1891.

	Inches.
Ansley, Custer County	8.19
Burwell, Garfield County	7.54
Dunning, Blaine County	9.12
Ericson, Wheeler County	5.39
Genoa, Nance County	8.48
North Loup, Valley County	7.82
Palmer, Merrick County	8.75
Ravenna, Buffalo County	9.29
Sargent, Custer County	7.46
Mean for nine stations	8.00

Thus a single month has furnished one-third of the normal amount for the whole year. A large percentage of this was concentrated in the last week of the month. I was in the Loup Valley at the time, and I can vouch for the accuracy of the reports. The rain fell in torrents, and the resulting floods and washing out of bridges and embankments caused the suspension of all travel, whether by rail or wagon roads, for several days. It is no doubt contrary to all precedents for an irrigation survey to be water-bound, but the fact is undeniable in this case.

Fortunately, I obtained a measurement of the Loup at Columbus, near its mouth, before the floods came on. I found 7,065 second-feet June 24, 1891. Judging from the appearance of the channel, and from the reports of old citizens who have seen the river daily for many years, this measurement, surprisingly large as it seems, is not much above the normal discharge of the Loup. This river is remarkable for the constancy of its volume. It never runs dry, never even runs low. The Platte, which on the same day was discharging, at Columbus, the enormous volume of 18,240 second-feet, often goes dry above the mouth of the Loup, but never below. Its miles of sands and gravels can absorb its own waters, but the steady and strong current of the Loup maintains itself even upon the wide, deep, and porous mass of materials in the Platte Valley. That this is no easy task appears not only from the drying up of the Platte for one or two months of each year, but also from the complete disappearance, at all seasons of the year, of certain small streams as soon as they enter the Platte Valley. They have a perennial flow and considerable volume in their course among the hills, but not sufficient strength to keep open a channel across the Platte bottoms. Lost Creek, in Platte County, is a good example of such streams.

The drainage of the Loup Valley is in one sense very incomplete. We have seen above that large areas are undrained. But if we refer to the percentage of the rainfall of the whole basin which flows out through the main Loup, and by that standard determine the completeness of the drainage in comparison with other hydrographic basins, we shall reach a different conclusion. Humphreys and Abbott, in their exhaustive report on the Mississippi River, found that it discharged 25 per cent of the rainfall of its basin. If the same percentage holds good in the case of the Loup we shall have 5,872 second-feet for its mean volume. All the indications tend to confirm the conclusion that this figure is certainly not above, though it may be somewhat below, the true average for the year. I found 1,193 second-feet more than this on the 24th of June. It is true that Humphreys and Abbott also estimated the drainage of the Missouri Valley at 15 per cent of the rainfall, and since the Loup is in that basin it would seem more natural to place its drainage on a par with its neighbors of the treeless belt. The valleys of the eastern tributaries of the Mississippi are well wooded, and the effects of a forest cover in retaining moisture and equalizing its flow are well known. Now, while it is true that the Loup region lacks a forest cover, it is also true that it possesses other means of conserving and equalizing the flow of moisture which are no less effective than forests. These means are the porous and uneven surface of the country and the great mass of absorptive and permeable Tertiary rocks lying upon a sloping floor of Cretaceous shales which are impervious, and into which the main Loup has cut its channel. It seems, therefore, entirely reasonable to compare the Loup, as to its average volume and the percentage of the rainfall discharged through it, with the streams of a forest region, and to estimate its mean volume at from 5,000 to 6,000

cubic feet per second. In a region where the rainfall is so considerable and so seasonably distributed, the irrigations required would be infrequent. We should probably be safe, therefore, in placing the duty of water as high as 200 acres per second-foot, so that the Loup would irrigate 1,000,000 acres of land, without reckoning upon the chance of using the same water more than once along the main stream and its tributaries. The same causes which combine to produce such remarkable results in the way of absorption of the rainfall, and the delivery of it to the springs and rivers in graduated quantities throughout the year, would also operate upon the water of irrigation. When spread abroad over the soil of the upper valleys a large percentage of it would enter the earth, after doing its work upon the spot where it was applied, and reappear in the springs and rivers below, ready for further use in irrigation.

The rate of movement of subterranean waters is an inquiry full of interest. In the hope of adding something to the meager data upon this subject I will record a curious phenomenon and its probable cause. By reference to the diagram above showing the curve of annual precipitation it will be seen that September is a relatively dry month, much drier than the summer months. Notwithstanding this decline in the precipitation, and quite independently of the state of the weather at the time, the Loup rivers quite generally *rise* in September. The increase in volume is slight, yet quite perceptible, and, coming as it does in a dry month and without rain at the time to account for it, it provokes much comment and curious speculation. The explanation is obvious. The maximum rainfall occurs in July. That portion of it which flows off on the surface raises the rivers at once, and may flood the lower valleys. That portion which falls upon the undrained area, which amounts to 35 per cent of the whole basin, and that portion which is absorbed in the drained areas, percolates slowly through the porous beds and reaches the rivers two months later producing the September rise. A rough estimate of the average distance traversed by these subterranean waters in the two months from July to September gives 20 miles, and consequently the very slow rate of one-third of a mile per day. This tardy rate of movement is an important factor in estimating the supplies which may be drawn from any subterranean source. There is a tendency to exaggeration in such estimates, somewhat akin to the general disposition to magnify the value of mines and all mysterious underground sources of wealth. Not only do underground waters move slowly, so that it is impossible to draw out their whole volume rapidly at one point, but a large percentage always remains in the rocks under all circumstances. Hence the fallacy of assuming that because the rocks *contain* a given amount per square mile, that whole amount is available for irrigation. Only by means of powerful pressure, or high temperature long maintained, could it all be expelled. Under natural conditions it is only the excess above that required for saturation which may be drawn out by subflow ditches or pumping.

As the seasonal distribution of the rainfall is highly favorable to agriculture without irrigation, so it is highly favorable to irrigation. It furnishes abundant water in the rivers at the time when it is needed. Rapid absorption and slow percolation combine to prevent disastrous floods on the one hand, and to maintain a steady volume in the rivers on the other hand. Thus the geological structure coöperates with the seasonal distribution of the rains to produce conditions highly favorable to agriculture in every form.

The entire absence of floods, consequently of a flood plain, and of the

type of valley structure resulting therefrom, which was mentioned above under the head of surface features, is due to the geological structure more than to the distribution of the rainfall. Heavy storms and deluges of rain occur just as they do in other regions, but the earth swallows up the water almost as fast as it falls, especially in the sand hills. Throughout the whole undrained area absorption and evaporation together dispose of the whole downpour; nothing is left for the augmentation of flood waters. Even in the drained areas the run-off is but a fraction of the whole amount precipitated. Evaporation and absorption claim their share in these areas also. Now, the percentage of undrained surface increases upward towards the head waters, ending in complete absence of drainage lines. The liability to floods diminishes in like manner and direction. Along the main Loup, and for some distance above the mouths of its tributaries, the mesh of drainage lines covers the whole surface, the run off is free and rapid, producing floods, flood plains, and valleys, whose sectional elements are of the ordinary type, shown above in Fig. 4. As we ascend the streams the marks of overflow gradually disappear, just in proportion as the undrained areas increase, and the valley section assumes the form shown in Fig. 3.

In a valley of this type there is the defect of a lack of rich bottom lands. Instead we may see alkali flats, sands, or gumbo. But all of these are capable of amelioration, and there are the compensating advantages that if the floods do not come to form rich deposits of river silt, neither do they come to destroy the labors of the husbandman. Furthermore, the rapid absorption which checks the run off and prevents floods forms vast stores of subterranean moisture, which maintain the steady volume of the streams, thus furnishing water in abundance to redeem the sands and alkali flats by basin irrigation.

IRRIGABLE LANDS IN THE LOUP VALLEY.

In this valley economic irrigation is even more rigidly restricted to the valley lands than in other parts of the State. The sand hills and the table-lands, whether pitted with lagoons or dissected into hills, each present peculiar and almost insuperable obstacles to irrigation. The valleys, on the other hand, are easily irrigated, lying near the drainage level so as to be cheaply supplied by means of short ditches. Furthermore, the valley land is sufficient in amount to absorb all the water.

The large map accompanying this report shows by hachures or dotted lines the bluffs which form the bounding walls of the valleys. All the land between these bluffs is irrigable land, provided it lies far enough below the heads of the streams. For the extensive natural meadows about the head waters there is no visible supply of water for irrigation, except from wells, and indeed they do not need any irrigation, being thoroughly saturated except in very dry seasons. The thousands of tons of excellent hay cut from them every year clearly indicates the best use to which they can be put.

Below this head-water region of natural meadows all of the valley lands are susceptible of irrigation and would be benefited by it. It is true that the valley lands differ greatly in quality, and respecting some of them doubts may be entertained whether they will ever repay the cost of irrigation or any other improvement. These differences depend upon the lay of the land and the nature of the soil. The best valley lands are smooth, gently sloping, with loamy soil and subsoil. Such land is abundant in all the valleys. By careful selection enough of it

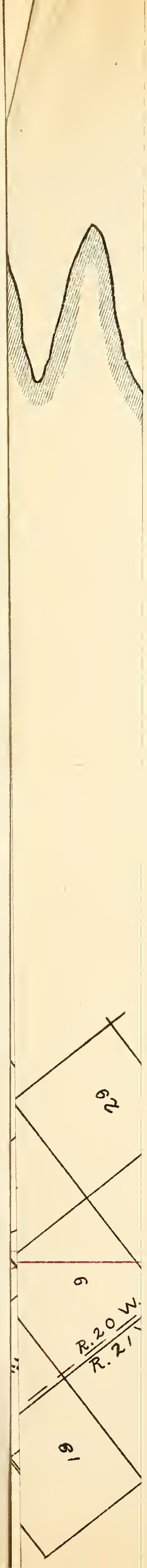

R. 20 W.
R. 21

Fig. IV Hicks

Fig. 14 Profile & Line across the Loup Rivers extending S.E. from Willow Springs.

may generally be found to utilize all of the available supply of water. But if there is not enough of such good land to take the water, or if the fortunate owners of such land should prefer to depend upon the rainfall, as they have done hitherto, then the waters may be utilized in another way, that is, to redeem the alkaline and sandy soils of the valleys. Water will cure the sterility of a sandy soil by the deposition of fertile sediment upon it; it will cure an alkaline soil by dissolving and washing out the alkaline carbonates. The success of both operations requires flooding, that is, covering the ground completely with water to a considerable depth in the nongrowing season. This is a distinct kind of irrigation. In Egypt, where it has been practiced successfully for ages, both for fertilizing and washing out alkalis, it is called basin irrigation; while the application of water to the soil in the growing season, the only kind of irrigation as yet practiced in this country, is called summer irrigation.

It may be objected that the reclamation of the sandy lands in the valleys will be difficult or impossible on account of the rapid waste of water by percolation, both in the ditches and fields. This waste would undoubtedly be considerable, but not fatal to success. I have ascertained in almost every case where the opportunity of examining the subsoil has presented itself that at no great depth in these valleys clay bands underlie the sand, and these would intercept the escape of the water by percolation. They are not wholly impervious, it is true, being loam rather than pure clay, but they will serve to retain the water sufficiently, and at the same time admit of a wholesome dregree of subsoil drainage. Once get the water to remain some time in the ditches and on the fields, and it will protect itself by its own sediment, so that each subsequent irrigation will be accomplished with less and less waste of water.

The total area of irrigable lands in the valleys of the Loup region is 1,013,760 acres. Outside of the valleys irrigation will be limited to small tracts supplied by wells too small and infrequent to make an item in the reckoning. The map, showing as it does the boundaries of the valleys, is therefore a map of the irrigable lands of the Loup Valley, amounting in round numbers to 1,000,000 acres. As we have seen above that the water supply under the favorable climatic conditions of this valley, which will admit of a high estimate of the duty of water, is just about equal to the task of irrigating 1,000,000 acres, we have a happy equilibrium of irrigable land and available water for irrigation.

AGRICULTURAL RESOURCES OF THE LOUP VALLEY.

The Loup Valley is highly favored by nature. Already, without irrigation and in spite of its recent settlement, having hardly completed its first decade, immense crops are produced almost every year, the crop failures being no more frequent than in any average agricultural region in the rain belt. The highly favorable distribution of the rainfall during the growing season goes far to account for the fruitfulness of this region. According to the statistical tables in the Annual Report of the State Board of Agriculture for 1889 the Loup Valley produced in that year 11,053,455 bushels of maize, 1,401,745 bushels of wheat, and 4,625,040 bushels of oats. The three largest items in the live-stock account were 62,819 horses, 156,850 cattle, and 134,268 hogs.

By utilizing the water to irrigate the good valley lands, and redeem and then irrigate the poor valley lands, this region may be made equal

to the choicest in the country in its fruitfulness and capacity to sustain a dense population. The unbroken table-lands have an excellent soil. Here deep and frequent tillage will take the place of irrigation. The dissected table-lands constituting the hilly districts (not sand hills) have also an excellent soil, in which the benefits of deep and frequent tillage must be the chief reliance for their amelioration. The natural meadows at the head waters of the streams will be a constantly increasing source of wealth, producing large crops with scarcely any other expense than harvesting and marketing the product. Even the sand hills may be utilized. The earthy nature of these sands, in contrast with pure silica, has already been mentioned, and its effect upon the retention of moisture noted. Its effect in making the sand hills fertile is equally important. Once get these sands to stop drifting and they may be cultivated with marked success. But the best use to make of them will be to clothe them with a forest cover. This will at once serve to break the violent winds, to anchor the sands, to protect the fertile basins which abound among the sand hills, and to improve still more the naturally excellent conditions of absorption and retention of moisture. Recent experiments under the direction of the Forestry Division of the United States Department of Agriculture* indicate the possibility of foresting the sand hills, though the magnitude of the undertaking, and the signal benefits certain to result from it, seem to demand Government aid. The closed basins and the more level spaces among these hills are already cultivated with success, and with the protection from winds and increased moisture resulting from a forest cover on the hills, these fruitful spots might be greatly extended and rendered far more productive.

The occupation of the country and all of the operations of agriculture will augment and intensify the excellent combination of natural conditions in this valley. The main Loup is distinguished among the rivers of the treeless belt for the large and constant volume of water which it maintains throughout the year. We have seen that this results from the geological structure and the uneven, highly absorptive surface of the country. Of these dominant physical conditions the geological structure and the main features of the topography are permanent, at least with reference to the events of human history and the operations of human industry, though they are not ever-enduring in relation to historical geology. The third element, porosity and absorptiveness of the surface, will increase by cultivation. Deep and frequent tillage of the table-lands and hill slopes will secure more immediate and complete absorption and retention of the rainfall. Irrigation in the valleys will spread out the waters and retain them longer, permitting them to escape only by evaporation, which will increase the humidity of the air and promote precipitation, or by slow percolation through the soil and subsoil. Lastly, the foresting of the sand hills, if that shall ever be happily accomplished by combined and persistent efforts of individuals, or by a liberal policy on the part of the national or State government, will do more than all other artificial operations to ameliorate the climate.

* What is Forestry? Bulletin No. 5, Forestry Division, U. S. Department of Agriculture, p. 40.

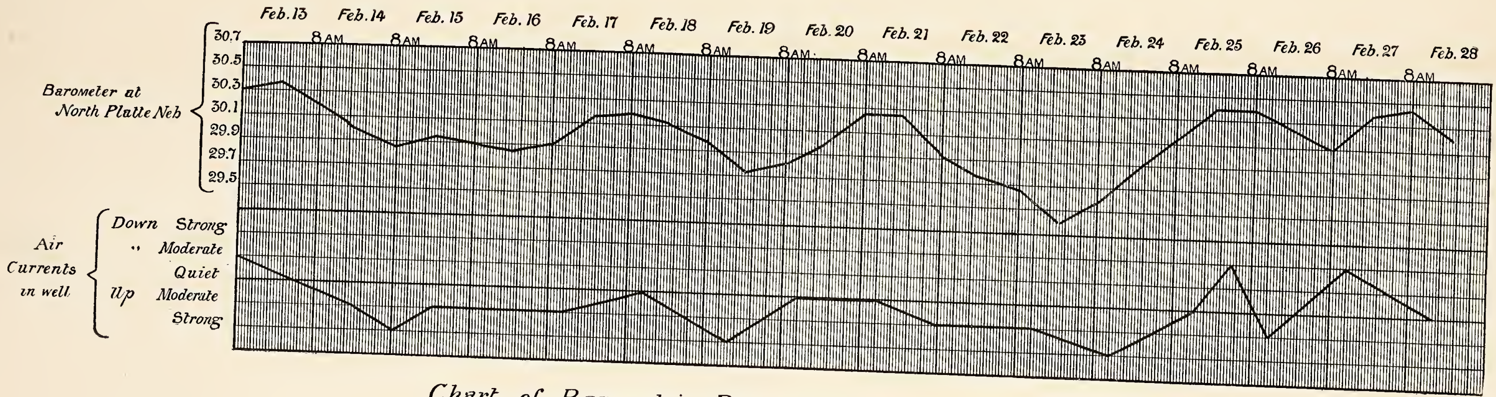


Chart of. Barometric Pressure as Compared with Currents of Air.

In the St. Elmo Well.

REPORT

OF

PROF. GARRY E. CULVER,

ASSISTANT GEOLOGIST FOR SOUTH DAKOTA.

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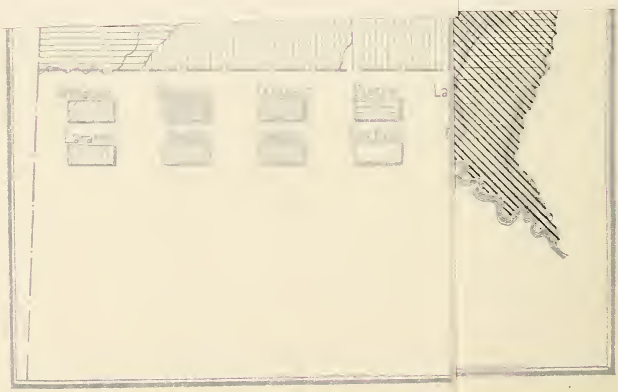
ILLUSTRATIONS.



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REPORT OF PROF. GARRY E. CULVER.

THE DAKOTA BASIN.

In a brief summary of the controlling geological conditions of this basin submitted at the close of last season's work the following conclusions were offered:

1. The basin consists of a low, broad synclinal, with its axis approximately north and south. The eastern edge of the basin is in the eastern part of the Dakotas, and the western edge is near the foothills of the Rocky Mountains.

2. Only the rocks of the Cretaceous series and the younger rocks are involved.

3. The Dakota sandstone is the water-bearing rock.

4. This rock is exposed along the Big Sioux River in South Dakota and further south. It dips gently to the northwest, and the surface rises in the same direction.

5. In the valleys of the Missouri, Big Sioux, James, and Vermillion rivers the thinned covering beds (Colorado group) allow the water to escape upward, and a series of artesian springs is formed. These springs extend from Chamberlin, on the Missouri, to Sioux City, Iowa. This leakage is thought to account for the diminution in the flow and pressure in the southeastern part of the basin.

6. The eastern border of the basin is approximately on a line running through Vermillion, Scotland, Mitchell, Iroquois, Clark, along the west flank of the "coteau," to the latitude of Andover, thence northeast to the State line.

The eastern border in North Dakota is not so clearly defined.

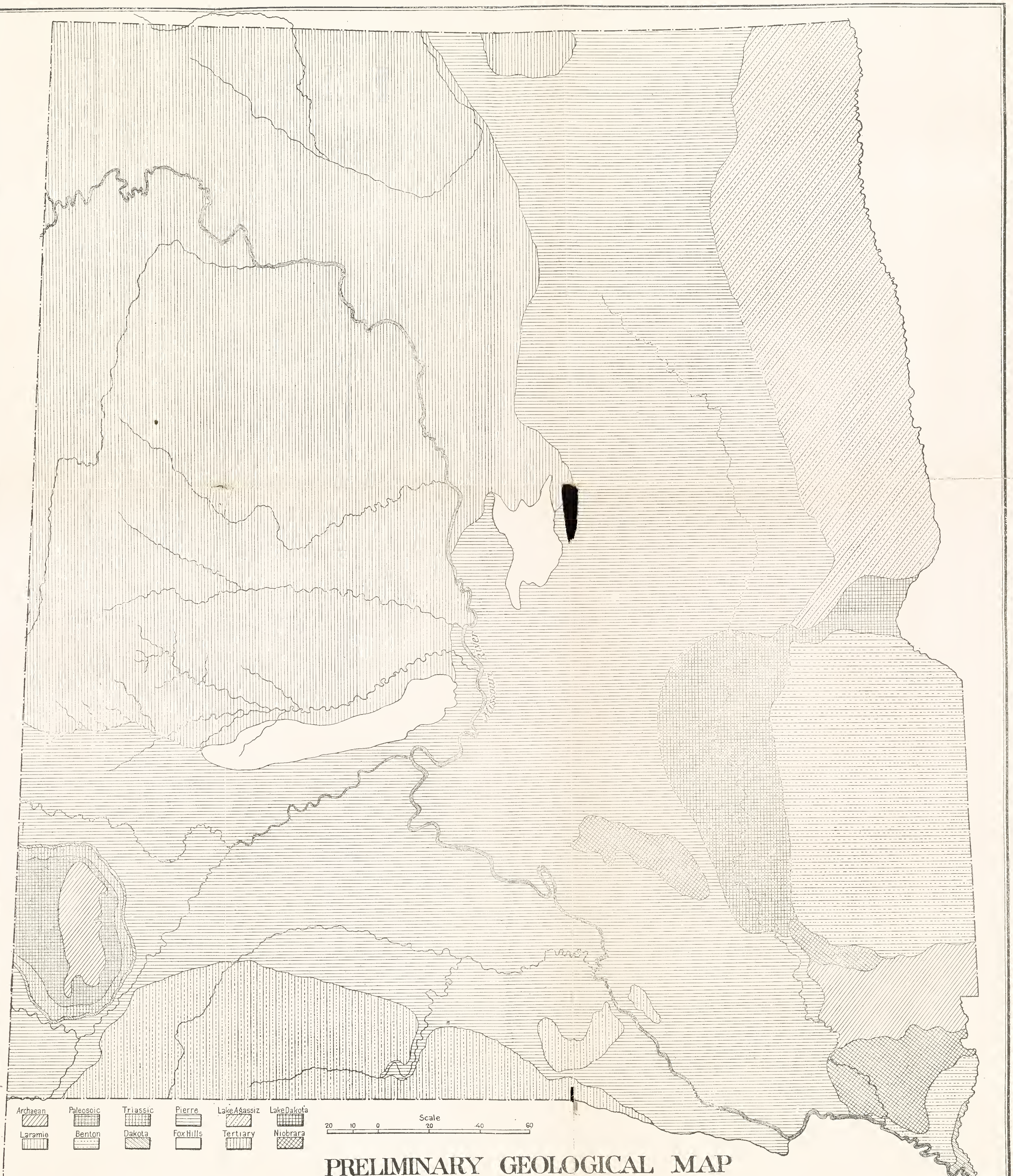
7. The wells of the Red River Valley are not connected with the Dakota artesian basin. The shallow wells of southeastern South Dakota are likewise unconnected.

8. While most of the deep wells are in the James Valley, that district is not to be regarded as the controlling factor in the problem as regards either the cause or the extent of the basin.

9. The source of the supply is the region along the base of the Rocky Mountains, where the Dakota either comes to the surface or is so thinly covered that meteoric water readily finds its way into it.

10. Whether the water will rise to the surface in the more elevated parts of the basin is at present a question. The pressure in the best wells in the James Valley is only sufficient to raise the water 2,000 feet above sea level.

While it will of course be understood that the evidence is not all in yet, it may be said that the work of the present season has tended in the main to confirm the positions taken last year. Some errors have been discovered and corrected, and the investigation considerably extended.



PRELIMINARY GEOLOGICAL MAP
of the
DAKOTAS
by Garry B. Culver.

Figur 1. Culver

ADDITIONAL GENERAL FACTS.

The Underlying Beds.—In the southeastern part of the basin the Dakota rests directly on the Archean. How far north or west this is true it is at present impossible to say, as the wells are only occasionally drilled to a sufficient depth to determine what does underlie the water-bearing rock. A well about 10 miles west of Tyndall, in Bon Homme County, showed the quartzite to be present there.

In the northern and northeastern parts of the James River district it is not at all improbable that either the Trias or the Carboniferous may be the underlying rock.

In the Red River Valley the entire Cretaceous series seems to be wanting, and the drill, after penetrating the lacustrine and drift deposits, enters the Red Beds, or possibly the red sandy shale of the Upper Carboniferous.

There is no geological break in the Cretaceous beds along the line between South Dakota and Nebraska. So far as structure is concerned, the basin may be considered as extending into Nebraska. In fact, a few wells in northeast Nebraska have been in operation for some time that are clearly in the same basin as those on the north side of the Missouri River.

The continuity of the beds of the Upper Missouri Cretaceous series is one of its marked features. The rocks are not only continuous and of great extent, but they are also unbroken and undisturbed throughout their whole extent.

Where they have been disturbed at all it has been by the thrusting up through them of masses of volcanic rock in the western part of the series. But even here, owing to their plastic nature, they have not been fissured nor broken by any of these uplifts, save in the immediate neighborhood of the disturbance.

These facts have an important bearing on the economic side of the artesian well question. They very nearly remove the underground uncertainty that is so annoying in the case of many artesian basins. In cases where the water-bearing rock is one of the older series, say the Potsdam, or one of the sandstones of the Carboniferous, the confining beds are often fissured in such a way that the rock ceases to be water-bearing in places where the continuity of the beds is unquestioned and all surface indications are favorable.

The water has escaped through the fissure to lower levels, and the basin, so far as water is concerned, terminates abruptly at the line of fissure. In regions that have been much disturbed, this is probably the cause of failure in a large number of cases.

In the present case, for the reasons already given, this cause of failure is almost entirely removed. The limiting causes here are the following:

On the southeast the water-bearing rock rises to the surface at such a low altitude as to allow leakage. In the same region the overlying impervious beds thin out to the southeast so much as to allow the water to escape upward, thus still further reducing the pressure and consequently the flow as this part of the basin is reached. It may be remarked here that in addition to the artesian springs reported last year in this region, it now seems probable that some of the shallow artesian wells in the northern part of Yankton and Clay counties at least may derive their supply from this same leakage. This fact was suspected last year, but at that time I had no evidence that warranted its publication. It seems that the water, after rising through the Cretaceous

beds to the Drift, runs into beds of sand, which are covered by impervious beds of clay, thus forming local artesian basins of small extent.

That this leakage is extensive is very probable. It seems to be greatest in the neighborhood of Yankton. At this point the covering beds consist only of the Benton shales and the Niobrara, or chalk beds. The latter are rigid enough to sustain fracture, and a small "fault" occurs in the beds just north of Yankton. The throw is a trifle over 4 feet. The Missouri River has removed about 100 feet of these beds from a strip over 2 miles in width. This strip is now covered by the silt of the river, and hides all leakage that may occur there. At Running Water, Randall, and Chamberlain, springs are seen rising from the bed of the river.

Were it not for this leakage, I see no reason why the most powerful wells should not be found in this part of the basin. The pressure at Yankton, for instance, ought to be 175 pounds, but it is only 52 pounds.

On the east the water does not fail until the real border of the basin is reached. On the north no tests have been made further north than Devils Lake. The northerly dip of the beds carries the Dakota so deep in the northern part of the north State that depth becomes the limiting element there.

The western part of the basin is yet unexplored. The question here is whether the water will rise to the surface of the more elevated portions.

Taking the wells of the eastern or James River district as a standard, the chances are that it will not, as none of these wells have force enough to raise the water to a greater height than 2,000 feet above sea level. Much of the country west of the Missouri River is from 2,000 to 2,500 feet above the sea.

If flowing wells are found in these more elevated districts, it will probably be due to one of the following causes: (1) The water-bearing rock may be found nearer to the surface there than it is farther east; (2) the sandstone may be coarser to the westward, thus lessening the friction, so that as the finer-textured portions are reached the water tends to accumulate, and as the surface is considerably lower than the supposed source the water may rise through the drill hole to higher levels than it would farther east; (3) there may be other water-bearing beds at higher levels than the Dakota sandstone that can furnish a flow to these regions.

Distribution of beds.—Last year I was unable to reach a conclusion in regard to the shale beds in the northern part of the Dakotas. I was rather inclined to call the surface beds Benton. More study has convinced me that they are either Pierre or else the whole Colorado and Montana group becomes one in one unbroken series of uniform character, so much like the Pierre that the record of an artesian well is not sufficient to warrant any distinction. The beds spoken of in my report last year as occurring at Milton are now known to be continuous with the undoubted Pierre on the Missouri at Forest City and above.

A small patch of the Fox Hills group was found in the region between the James River district and the Missouri in North Dakota. The eastern border of the Laramie has also been roughly determined. The Tertiary beds are put in rather at random on the map accompanying this report, as they lie almost wholly in the unstudied portion. They have been seen at several points, but not examined much.

Doubtful districts.—The region lying between the Missouri River and the James River district, known commonly as the "Coteau du Missouri," was examined to some extent, with the intent of finding if pos-

sible whether the artesian conditions extended over that region. The Coteau seems to me to be simply that part of the Great Plain cut off by the Missouri River from the western portion, and made more prominent by two natural causes. The first of these is the erosion of the James Valley. As in the case of the Red River of the North, the Cretacean beds have been largely carried away by an ancient erosion, occurring before glacial times at least. This erosion made the bed of Lake Dakota, the draining of which left the present James Valley. Climbing up out of this old lake bed to the west, say, in the altitude of Aberdeen, we reach in the western part of Edmunds County an elevation of 2,000 feet. From here west the country is a level plain with a very constant elevation. About 10 or 15 miles from the Missouri the descent into its valley begins. It is much more abrupt than the ascent from the ancient valley on the east. In fact, except in the valleys of the streams, the whole descent of 350 feet is made in less than a mile. The streams have cut more gradual slopes, but their erosion is slight. Crossing the deep gash in the plain made by the Missouri and climbing out, we come again upon a comparatively level plain, but very little if any higher than the one we left on the east side of the river. The "Coteau," then, is a hill of erosion, made prominent by having both flanks carried away. Another feature adds to its prominence. The summit of this ridge is covered in many places by moraines. These have not eroded regularly like the sedimentary beds below them, but have as usual been cut into peaks and low, irregular hills, which blend with the slopes of the valleys in such a way as to seem to be a part of the original structure.

As to the probability of success in obtaining an artesian flow here, the question is the same as it is on the west side of the Missouri farther south, which I have already discussed. It is simply a question of elevation. There are no forbidding geological conditions aside from that. The structure is the same here as in the regions to the east. The erosion simply has not been so great, that is all.

The water supply other than artesian in this region is somewhat interesting. Under the drift and other recent deposits is another and older land surface. This surface had been eroded and cut into valleys and ridges like the present surface. The old buried stream-beds and beaches, filled with sand and gravel, are the sources of the present water supply. From facts furnished me by Mr. Barr, of the Chicago, Milwaukee and St. Paul Railroad, I conclude that these old streams ran in a north and south direction. The depth to which these beds of gravel have been covered varies from 20 to 40 feet. The average is about 25 feet. The water is always of good quality in these gravel beds, and the supply never fails. Wells dug at any other place penetrate the blue clay after passing through the drift, and are often sunk to the depth of a hundred or more feet without finding water, and when it is found it is invariably of poor quality.

NATURAL SUBTERRANEAN RESERVOIRS.

Notwithstanding all that has been said about the subject of irrigation and artesian wells, there is a great deal of misapprehension and error in reference to some of the fundamental principles of the subject. It is still commonly believed, for example, that flowing wells can be had anywhere by going deep enough. The favorite idea concerning the source of artesian water is that of an underground lake. The only formidable

rival of this view in the Dakota basin is the notion entertained by many that the water comes from the Missouri River through an underground channel. Without discussing these views at all, I simply give here a brief account of the character of these reservoirs as they occur in the Dakotas.

As in other regions they are of three kinds, as follows:

(*a*) Gravel sheets and streams at shallow depths.

(*b*) Sand and gravel beds, under this beds of clay.

(*c*) Sandstones and conglomerates at various depths in the great sedimentary series.

Over a large portion of the Dakotas, and, to a less extent in Montana, under the soil and drift or other recent deposit, another and older land surface is found at varying depths. This, like the present surface, was eroded by streams and dotted by lakes, which have left their record indelibly fixed in the geological history.

One part of this record consists of long lines of gravel, generally narrow, but extending for miles in one direction. These are beach lines of former lakes. They are easily distinguished from the other portion of the record, which consists also of stretches of gravel beds, by the fact that they are straight for long distances, and when they do curve it is in the regular smooth fashion of a lake shore at the present time.

The other part of the record consists of more sinuous and uneven lines, or beds of sand and gravel, marking the courses of ancient streams, the accompaniments of the lakes just mentioned. From such evidence as I was able to collect I infer that the general course of these ancient streams was north and south.

These gravel beds are at various depths in various parts of the country. In the district lying between the James River district and the Missouri River the average depth is 25 feet. They are invariably found to contain an abundance of excellent water. They are the source of the ordinary shallow wells of the country.

It is often a strange and unaccountable thing to a settler in the region mentioned to find that his neighbor on the east or west finds abundance of good water at comparatively shallow depth, while he digs to twice or three times the depth finding only blue clay and little or no water, and that little of poor quality. He has simply been digging on the banks of the former stream, in beds that never contained water and are nearly impervious to it, while his more fortunate neighbor has sunk his well into the bed of the ancient stream, now filled with water-bearing sand and gravel.

The natural supply for these sheets is the rainfall of the region filtered through the soil and drift, which has buried and hidden the old surface from sight.

The districts in which the conditions under (*b*) exist are more limited. In these cases, after the beds of sand and gravel had been laid down, there was spread over them a continuous layer of clay, and usually more drift with other deposits, and over all the soil. The clay cover is sometimes more extensive than the sand bed, usually so indeed; and when it covers the lower portion, leaving the upper part covered only by pervious beds, we have the requisite conditions for a flowing well, which may or may not deliver its water at the surface. This will depend on the extent of the bed of sand. Such conditions as are here described occur in several parts of the Dakotas.

The flowing wells of the Red River Valley belong here. The cretaceous shales were completely removed from that valley by preglacial erosion, a considerable bed of sand was spread over the region, and

then, as a result of some physical change, a bed of blue clay was brought down and spread over the whole valley. Since then the glacial drift has been spread above the clay, and the lacustrine deposit of Lake Agassiz over that, and, finally, the soil covers all.

Probably through leaks in the thin and elevated western edge of this covering, meteoric water percolates and collects in the sealed-in sand of the old buried surface of the valley.* Other districts, similar to, but smaller than this one, are found in various parts of the country. The shallow wells of Miner County, S. Dak., as well as those of Lincoln and Turner counties, are examples of flowing wells due to such conditions. So far as I know these wells are confined to regions that have a considerable deposit of glacial drift upon them.

The supply of such wells is necessarily limited, and the flow and pressure usually small. They furnish water suitable for domestic purposes, and in quantities sufficient for stock farms, but not large enough for extensive irrigation.

The greatest natural reservoirs are found in the beds of sand and gravel constituting part of the great ancient series of sedimentary rocks. All rock, without exception, contains water. The amount carried varies with the texture of the rock. The hard, close-textured rocks carry but little less than 1 per cent, while the softer, more open-textured varieties may carry from 20 to 30 per cent. A cubic foot of sandstone may thus contain from 1 to 2 gallons of water. When such a bed of sandstone lies between two impervious beds of rock, and has one of its edges extended up at a slight angle, and reaching beyond the covering bed so as to receive a good supply of meteoric water, we have the simplest conditions for an artesian flow. All the great artesian basins, whether water or oil be the product, have this structure or some modification of it. The water-bearing rock is not always sandstone, however.

In this region the Dakota sandstone is believed to be the water-bearing rock from which all our artesian wells draw their supply. It is a rock of great extent and considerable thickness, and is a good water-carrier. As already explained, its western edge is along the flanks of the mountains and around the outer edge of the Black Hills, where it has good opportunities to absorb large quantities of water. Its eastern edge is exposed in eastern Nebraska and northeastern Kansas, as well as in the southeast corner of South Dakota. Aside from these exposures, its easterne dge is buried by the overlying Colorado beds. Probably, were it not for this fact, since the western edge of the Dakota is 2,000 feet above the eastern edge, the water would not accumulate, but would run out at the lower eastern edge as fast as it could run in at the western. One of the most interesting as well as important questions connected with this rock is the extent to which the water accumulates, that is, how far toward its source the water has saturated the rock.

In this connection a letter received from Mr. L. H. Hole, president of the North American Loan and Trust Company, Chicago, is interesting:

CHICAGO, ILL., *August* 10, 1891.

DEAR SIR: Replying to your favor of the 23d ultimo, which awaited my return from New Mexico. In the fall of 1890 the Huron waterworks well was found to be on the decline. This led to numerous observations made at short intervals from that time up to May, 1891. The observations were made on the two city wells, the Day and Harrison, and the Consolidated Irrigation Company wells, 8 miles north of Huron. I have not the figures in my possession, but will send and get them if they

*Mr. Upham thinks the supply for some of these wells comes from the Dakota sandstone.

have not been destroyed. From these observations we found that there was a gradual decline in the pressure of each one of the wells, each showing a sympathy (to a common cause) of about the same pound pressure. This diminution continued on until, I think, some time in December, when it came to a standstill, and from that time until May there was a continual increase in the pressure. The same increase was noted in each well, or nearly so, until in May or the 1st of June, when the highest pressure was reached. Since that time we have made no observations, but I was at Redfield when the Government agents tested the Redfield well in the middle of June, and it was found to be as high or a little higher than ever before known. From these observations I deduce the following conclusion: That the source of water is the Rocky Mountains, and as the snow melts and the rain ceases as it does there in the summer and fall, the pressure is diminished. While some may object to this theory as indicating a limit to the supply, to me it is encouraging, for so long as the rain falls and the snow melts in the mountains, we will have this supply in abundance.

Yours sincerely,

L. H. HOLE.

Prof. G. E. CULVER,
Vermillion, S. Dak.

Should further observation confirm this oscillation of pressure reported by Mr. Hole, it would indicate a pretty free communication through the whole extent of the Dakota sandstone, or else that the water does not accumulate far back toward the source.

THE SUPPLY OF WATER.

Source.—A multitude of opinions as to the source of the water have been from time to time published, and each seems to have its believers. Among them are the following: 1, the Great Lakes; 2, the lakes of Canada; 3, Devils Lake, North Dakota; 4, great subterranean lakes; 5, the Missouri River.

The fact that these opinions find currency in the public press even in the large cities, leads me to think that it may be well to state here briefly the objections to them and the reasons for thinking that the water comes from an entirely different source. First, the Great Lakes are simply out of the question; their elevation is not sufficient by at least 1,000 feet; second, the Canadian lakes are thrown out for the same reason; third, Devils Lake is about 25 feet lower than the surface of the ground where the artesian well at the town of Devils Lake is located, and the well will throw the water 40 feet higher still. Without saying anything further, it is sufficiently evident that this lake can not be the source; fourth, great subterranean lakes would have to be either very numerous or very extensive to supply all the wells, as they are scattered over a region 350 miles long and at least 100 miles wide. Besides, the only known force that could lift the water to the surface in opposition to gravity is either gas pressure or the pressure produced by the collapsing of the plastic strata covering the reservoirs. In the first case the pressure would not be likely to be maintained at such an even tension, and gas would be likely to escape with the water. In the second case the collapsing of the cover would be apt to show itself in other ways, and the difficulty of supplying so many underground lakes is the same. There seems to me to be no evidence of the truth of this opinion; fifth, the Missouri River, in order to supply the wells, must find its way through the covering beds at a point in its course where its elevation is over 2,000 feet. Its elevation at Williston, in the northwestern part of North Dakota, is 1,869 feet. Hence we must go farther up stream yet. About at the mouth of the Milk River the desired elevation is obtained. This is 150 miles west of the east line of Montana.

At this point the bed of the Missouri is separated from the Dakota sandstone by the whole thickness of the Pierre, Niobrara, and Benton groups, a total thickness of probably not less than 2,000 feet of almost impervious beds. It seems to me that it is putting it mildly to say that it is highly improbable that any such leakage occurs here as would be necessary to supply the whole artesian basin.

Partly from the fact that none of these sources seem adequate to the case, and more because the Dakota sandstone either crops out or comes near the surface along the foothills of the Rocky Mountains, the writer has long been of the opinion that the source must be looked for in that direction. The sandy region in northwestern Nebraska is a good collecting area, but it is probably unable to deliver its water to the Dakota sandstone, being prevented by the thick, impervious beds of the Benton and Niobrara, and perhaps also the Pierre.

Amount.—On this point there is yet but little evidence on which to base a judgment. The most important testimony is furnished by the wells themselves. The fact that these have, many of them, been flowing for five years and yet show no diminution of either flow or pressure, points to an abundant supply, but does not prove it. Further evidence in the same line is found in the large number of wells now flowing and in the fact that the new ones have just as strong flow and pressure as those had which were bored earlier. Further than this, if the theory of a Rocky Mountain source be true, the supply is not only *copious*, but *constant.*

THE BLACK HILLS.

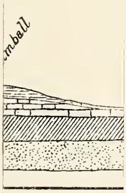
About three weeks were spent in a general reconnoissance of this region. The main question was the determination of the relation of the drainage of the Black Hills to the supply of the Dakota Artesian Basin. Incidentally some other observations were made relating to some of the other objects of this investigation.

In order that the account may be as intelligible as possible, a brief general description of the structure of the hills is here given. With the rising of the Rocky Mountains—whether that event was synchronous with the Black Hills uplift or not—the whole plains area was tilted slightly to the east for a long distance eastward from the mountains.

The Black Hills have been thrust up through this gently sloping plain. The axis of the uplift is approximately north and south. If the movement was a comparatively sudden one, the huge mass of strata uplifted formed a great ridge or elongated mound 10,000 to 15,000 feet high and from 80 to 100 miles long from north to south, the width being not more than 50 miles. This mound was composed of the whole geological series of rocks, with the possible exception of the Tertiary. Since its upheaval the top has been cut off by erosion to its present condition and elevation.

From the appearance of the rocks, as well as from analogy, it seems more probable that the rising was slow and that the hills have never attained the elevation required by the former supposition. At any rate, the whole sedimentary series, from the oldest Paleozoic to the youngest rocks here represented, has been removed from the axial area, leaving the surface exposure as follows:

In the central or axial area are the Archæan schists and slates, occupying a tract about 60 miles long and 10 to 25 wide, the greatest extent being from north to south. Surrounding this Archæan area, in rude,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1 Paleozoics
2 Triassic (Red Beds)
3 Jurassic
4 Dakota
5 Colorado {Niobrara / Benton
6 Montana - (Pierre only)

Fig. II. Ideal section across South Dakota on a line passing through Sioux Falls, and Rapid City.

Length of section 385 miles

concentric bands, are the sedimentary beds of the Paleozoic and the Mesozoic rocks, dipping away in all directions from the Archæan, but at constantly lessening angles, with some local exceptions, until a few miles out on the plains the beds are so little disturbed as to appear level to the unaided eye.

Not only do these beds appear in concentric bands, but each series forms a wall with its steeper face inward; so that as one travels toward the center from any point without, he ascends a long, gradual slope on the back of the Cretaceous beds, which ends in a short, abrupt descent to the next series, which in like manner rises toward the central portion of the hills and terminates in a steep wall, from the foot of which, rising gradually, the next older series appears, each with a little steeper ascent, until finally the Archæan is reached.

This is the result of the combined action of the forces of upheaval and of erosion, probably acting together through long periods of time.

Present Topography.—The schists and slates of the Archæan region seem to have yielded to the attacks of time more readily than the younger sedimentary beds. As a result these latter rocks, especially the Carboniferous limestone, rise considerably above the Archæan area, except in the case of the peaks of the latter. The peculiar structure already described brings the drainage squarely against each formation in turn, from the Potsdam to the Tertiary.

The Archæan schists have been cut into peaks, ridges, gulches, and valleys, mostly well wooded in the northern hills, but with more numerous grassy, park-like openings in the southern part. The streams which flow down these valleys have cut through the surrounding wall of Paleozic rock, carving a series of deep and picturesque cañons, whose walls afford a fine exposure of these beds, and have met and overcome in succession the various other walls already spoken of, until finally they emerge from the foothills of Dakota sandstone and start across the gently sloping plain to the Cheyenne River.

A fairly good idea of the general topography may be had by imagining a series of rudely oval concentric valleys surrounding the inner Archæan nucleus and cut at right angles by the cañon and more open valleys of the streams. Of course the valleys are not at all regular in either case, but they are nearly enough so to make the illustration serviceable. Perhaps the most prominent topographical features are the granitic peaks, the outer water wall of Dakota sandstone, and the Red Valley. The cañons of the Carboniferous zone are very picturesque, their walls rising abruptly from 200 to 500 feet, and perhaps higher in some places. The Red Valley is a beautiful grassy zone, from half a mile to 3 miles wide, completely encircling the hills just within the wall of sandstone previously mentioned. It is supposed to be of Triassic age.

Drainage.—Probably nine-tenths of the streams flow toward the east. Those that flow down the shorter western slope are also much smaller than the others. Whether this is due to the original structure and topography, or whether the precipitation being more copious on the eastern slope has shaped the topography to this result, may be questioned. It seems likely, however, that the tilting of the plains to the east helped to start the more rapid erosion of the eastern slope, and that this tendency was favored, and still is, by the greater rainfall of that side.

It is evident that whatever course the streams take in coming down from the hills they must all flow east on reaching the plains. This is equally true of the water flowing in them.

The streams are all formed by springs that rise in the lower edge of the Archæan area. These springs are formed by the rain which sinks into the thin stratum of soil covering the rocks in this inner region. The water runs down the inclined surface of the schists until it comes out in the sides of the ravines and gulches. These springs are all soft and very cold.

That some of the water finds its way into even the Archæan rocks is evident from the fact that at the Homestake mine a pump that lifts two barrels at every stroke is kept running day and night to keep the mine free.

By the time the streams leave the Archæan area they have attained considerable size. They flow swiftly down through the cañons cut in the Paleozoic rocks, and on reaching the Carboniferous limestone most of them sink, and all of them lose considerable water. This sinking of the streams is one of the marked features of the hills drainage. The only streams which do not disappear are the Redwater, Spearfish, and Rapid creeks; Whitewood and Battle creeks do not disappear, but formerly did so.

A suggestion made by Newton in 1875 has been realized in recent years. He said: *

> Possibly, after the work of active mining has been pursued in the valley for some time, sending down the creeks large quantities of sand and fine mud, some of them will become running streams out on the plains.

The muddy water from the stamp mills of the Homestake Mine has stopped the leaks in the bed of the Whitewood Creek, and a heavy flood is said to have done the same for Battle Creek.

The creeks, so far as my observation extended, all sink at the same geological horizon. As mentioned before, some water is certainly absorbed by all the rocks, but the streams grow constantly larger until they reach the base of the Carboniferous. Here they begin to shrink, and within a distance of from a half a mile to 2 miles they entirely disappear. Elk Creek, at the time of my visit, ran beyond this limit and disappeared in the débris at the mouth of the cañon. I was informed, however, by Mr. Runkel, who lives on his stream near the base of the Carboniferous, that the stream retreats up the valley to his place every season after the usual time of high water, and that it is sometimes dry even farther up than that.

As to the volume of water carried by the streams, I am able at this time to give the figures of a portion of them. I measured the flow of a large spring on Boxelder Creek (Dotys) in the following manner: Depth of stream, 6 inches; width of stream, 3 feet. Its velocity is such that stones weighing 10 or 12 pounds dropped gently into it are carried rapidly down the stream. According to the law of running water the velocity of this stream can not be less than 5 feet per second, which gives a flow of 7½ second feet, or 3,360 gallons per minute. As near as I could judge, the flow of the creek just above the junction with the stream from the spring was at the time of my visit—June 15—about twice the flow of the spring. The total flow, therefore, of the stream and spring is 22½ second feet, or in round numbers 10,000 gallons per minute.

I measured the flow of one branch of Spring Creek accurately, and found it to be 1,000 gallons per minute. I judge this branch to furnish less than one-fourth of the whole stream. If this is correct, the whole flow is not less than 4,000 gallons per minute.

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* P. 124, Geology of the Black Hills.

Fall Creek, in the southern hills, has been carefully measured at the point where it crosses the Dakota sandstone, and found to have a flow of 30.65 second feet, or 13,792 gallons per minute. This measurement was made by Mr. Quarnberg, of Cascade.

From Mr. Broughton, chief engineer of the Dakota, Wyoming and Missouri River Railroad at Rapid City, I obtained the flow of Rapid Creek, measured at the point where it enters the Red Valley, and before it has received the flow of one large and several small springs. The flow, as given at this point by Mr. Broughton, is 49.4 second feet, or 22,230 gallons per minute. This amount must be increased by fully 1,000 gallons to include the whole flow of the stream.

Rapid Creek is the largest of the streams that take their rise in the hills. No other streams were measured, nor measurements obtained. There are about twenty-seven streams in all. Only a part of them continue as flowing streams clear out to the plains.

Springs.—In speaking of the streams I have incidentally mentioned the springs. There are two distinct groups of these. The first, or upper group, consists of a great number of small springs of almost pure soft water, and of very low temperature. This group is confined wholly to the Archæan area, and is the source of the streams of the hills. Their origin has already been described. Even at altitudes as great as 6,000 feet these springs occur, and at one point on the Fort Pierre and Black Hills Railroad a little lake, spring fed, stands at a constant level all the year round, in a slight depression in the schists, 6,000 feet above the sea and apparently above all but a few peaks in the immediate neighborhood.

Near the top of the Carboniferous, at a level some 400 feet lower than the one at which the streams sink, occurs the second or lower series of springs. These usually rise in the valleys of the sunken streams. They are of large size, have an average temperature in the northern hills of about 50° F., and are somewhat mineralized. No analysis of them has been made, so far as I know, but from the fact that they come up from the limestone of the Carboniferous, and the further fact that in all probability the water is the same as that which disappeared in the beds of the streams at the base of the Carboniferous, salts of lime are probably the chief ingredients. I have already spoken of one of these —Dotys, on Boxelder Creek.

In the valley of Rapid Creek are several more of this group. The Claghorn group is the most important of these. This group consists of, perhaps, half a dozen springs of different size, but otherwise much alike. Their temperature is 50° F., and their combined flow is 16.9 second feet or 7,605 gallons per minute.

About 3 miles from this group is another large spring in the same valley, the Leedy Spring. It is very much the same in all respects, so far as a cursory examination could determine. The water is piped to Rapid City, which place it supplies with water for all purposes, and there is an overflow from which I estimated at least 500 gallons per minute. The entire flow of the spring, with some small ones that come out along the banks of the stream, can not be less than 3,500 gallons per minute.

In the southern hills at Hot Springs, from the same horizon, a series of hot, or rather warm, springs come forth. The temperature of these springs varies from 70° to 92° F. The flow of the largest one has been measured by Quarnberg, who makes it 400 cubic feet per minute. The water of this spring is now used to supply the large plunge-bath recently built there. The size of this bath is 50 by 200 feet and 4 feet

deep. The proprietor told me that the spring would fill the bath in about two hours. This gives 333½ cubic feet per minute, and, as there is considerable leakage, agrees fairly well with Mr. Quarnberg's more careful measurement.

The temperature of this spring is 88° F. at the point where it enters the bathing room. The combined flow of all these springs here is 1,232 cubic feet per minute, or 9,240 gallons per minute. They are much resorted to by invalids and others both in summer and in winter.

At Cascade, in the extreme southern hills, occurs another group of slightly warm springs. Their temperature varies from 65° to 70° F. The largest of the group has a flow of 228 cubic feet per minute (1,695 gallons). The total flow of this group is 1,260 cubic feet per minute (9,450 gallons). Preparations are being made to utilize this water for a similar use as those at Hot Springs.

What the cause of the higher temperature of these springs is I do not know. Volcanic activity has been greater farther north in the hills; in fact, these warm springs are entirely outside, south of the area showing lava at the surface.

These springs are thought to be more highly mineralized than the others. The following analyses have been made for the proprietors by Chicago chemists:

Minnekata Spring.

	Grains.
Silica	2.464
Peroxide of iron	Trace.
Calcium sulphate	16.352
Magnesium sulphate	4.320
Sodium sulplate } Potassium sulphate }	25.620
Sodium chloride and potassa (*sic*)	13.790

Mammoth Spring.

Sodium sulphate	23.262
Potassium sulphate	5.627
Calcium sulphate	36.212
Calcium chloride	5.588
Ammonium chloride	0.029
Magnesium chloride	4.114
Magnesium nitrate	0.302
Magnesium phosphate	0.099
Magnesium carbonate	3.505
Ferric oxide	0.149
Alumina	0.271
Silica	1.548

Lakota Spring.

Sodium sulphate	8.824
Potassium sulphate	3.333
Calcium sulphate	16.290
Calcium chloride	8.499
Ammonium chloride	0.049
Magnesium chloride	3.140
Calcium phosphate	0.311
Magnesium nitrate	0.150
Magnesium carbonate	3.044
Iron sesqui-oxide	0.260
Alumina	0.021
Silica	0.830

The analyses of the Mammoth and of the Lakota were made by Prof. Charles Gibson, of Chicago; that of the Minnekata by Prof. G. A. Maringer, of Chicago.

The predominance of the sulphates of the alkalies and the alkaline earths suggests a relationship with the water of the artesian wells of eastern Dakota.

The per cent of saturation is not so high in the case of the springs, but the high proportion—average 68 per cent—of the salts which constitute the chief mineral ingredients of the artesian water is certainly significant.

Rainfall of the hills.—The area of the Black Hills region is about 5,000 square miles. The average annual precipitation is 20 inches. This is 7,260,000,000 tons of water.

The usual statement made in regard to rainfall is that one-third is absorbed by the soil, one-third runs back to the sea, and one-third is evaporated.

In the Black Hills the conditions are, as I have shown, very favorable for absorption. Evaporation is also very rapid on account of the dryness of the atmosphere. Of the amount absorbed by the rocks it is evident a large amount is returned to the surface through the large springs. No springs occur outside the outer rim of the Carboniferous zone. This leaves a broad band extending outward to the junction of the Dakota with the Colorado, on which the precipitation either falls directly upon the Dakota or upon the impervious beds which slope toward the Dakota. This rock thus has an unusually good opportunity to absorb water. I estimate that 100,000,000 tons annually fall upon this rock directly, and if only one-fourth is absorbed it receives 25,000,000 tons.

But all the streams that leave the hills cross this same rock. What portion they absorb it is impossible to say, but the amount must be considerable.

From the fact that so many of the streams sink into the lower beds of the Carboniferous, and the further fact that so many large springs come from the upper beds of the same formation, it seems quite probable that the streams are the source of the springs. Whether all the water that sinks is brought back in this way is a question. If it is not, what becomes of the excess is a more interesting question still. Suppose it follows the dip of the rocks eastward. One of the three results may follow:

(1) The rocks may change their dip to the southeast, and thus carry the water out of the district entirely.

(2) The rocks (Carboniferous) may pinch out to the east before the overlying Trias, which is more impervious, and this would result in keeping the water from passing to the eastern portion of the basin, and would cause an accumulation in the Carboniferous beds.

(3) It may be that the reverse of the last case is true and the Trias pinches out first. In this case the Carboniferous would pass the water onto the overlying Jura sands, or, if these be wanting, to the Dakota, which* is continuous over the entire southern part of the basin at least.

Any one of these three cases seems to me possible. What data have we for determining which is most probable? In the eastern part of South Dakota neither the Carboniferous nor the Trias occur. Both pinch out, but which one first we do not know. This evidence is, therefore, negative. The Carboniferous rocks in Nebraska dip east-southeast. This would favor the first view. In North Dakota both the Carboniferous and the Trias occur, but neither is water-bearing.

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* In outcrops in Nebraska and Kansas, the Dakota does rest upon the Carboniferous, as was long ago pointed out by Lesquereau.

While it is thus evident that we have too little evidence for a conclusion in this matter, a fragment from the report of Prof. Hicks, made last year, is suggestive. In speaking of the flow from the Carboniferous in Nebraska he says: "Contrary to what one would naturally expect, the limestones yield more water than the sandstones." He does not report any strong flow, however, from this horizon.

RECAPITULATION.

(1) The total amount of water that falls on the region here discussed is about 7,250,000,000 tons.

(2) Fully 100,000,000 tons falls on the Dakota sandstone. Under the favorable conditions existing it is probable that one-fourth, or 25,000,000 tons, is directly absorbed by this rock.

(3) The water absorbed by the soil and the rocks in the upper part of the hills is largely returned to the surface in the form of springs.

(4) The streams either all sink or lose considerable water in the lower beds of the Carboniferous.

(5) The water which sinks as mentioned in 4 is probably the source of the large springs. It is uncertain whether all the sunken water returns to the surface again in this way.

(6) The number of springs and the fact of their great increase in size in the lower or Carboniferous group indicates that the water which sinks into the older rocks does not penetrate to any great depth, but that while running down to lower levels it is constantly rising in the geological scale, appearing successively in the Archæan, Silurian, Carboniferous, with steadily increasing volume.

(7) All the drainage of the Hills crosses the Dakota sandstone, which thus receives a second accession.

(8) The Carboniferous limestone may carry out of the district a portion of the water absorbed, or it may pass it along to the Dakota sandstone, thus giving it a third supply.

(9) The water of the streams, after escaping from the hills, is perhaps capable of irrigating 500,000 acres of land. (About 50,000 acres are actually under such irrigation at present.)

(10) The main question, *i. e.*, the relation of the drainage of the Black Hills to the artesian supply, may be safely answered by saying that the Black Hills contribute quite largely to the supply; and the Black Hills in this relation may be considered as an outlier of the Rocky Mountains.

TEST WELLS.

The region between the James River District and the Missouri River in both Dakotas has only been hastily and incompletely examined. Enough has been determined to show that it is a region in which test wells are needed, as only actual trial can determine whether the water will rise to the surface or not. There is no reason to doubt that the water is here. The region has an elevation of 2,000 feet above the sea. This is an important district, and the people are much interested in irrigation. Two wells, one, say, at Bowdle, Edmunds County, S. Dak., and the other at Steele, Dawson County, N. Dak., would settle the question for a large district.

In South Dakota, west of the Missouri, in the region between Pierre and the South Fork of the Cheyenne River, no examination was made this season. Many settlers are going in there, and the water question is

to all of them a most important one. Two wells, properly located, would determine most satisfactorily what could be done there.

A third district is that region lying between the forks of the Cheyenne and the Black Hills. Perhaps a single well would be sufficient here. A test well here would have more than a local value, as it would not only show whether the water will flow at so high an elevation, but also so near the same. A successful well here would mean much as to the volume of supply.

It would also have a very great local value, as the water from the streams, although not yet fully utilized, is not sufficient for the needs of the district.

Many stockmen would put down wells if assured that a flow could be had.

A fourth district is found in western North Dakota and Montana. In the latter State but little work has yet been done. The question here is whether there is another water bearing rock at a higher level than the Dakota sandstone. It is not to be expected that flows like those of the James River district will be found, but water sufficient for domestic and stock use may be in the sands of the Laramie.

As already intimated, the question of prime importance relates to the adequacy of the supply. Wells are rapidly multiplying, and the size of them is also increasing. At Yankton, S. Dak., a 12-inch well is now in progress of construction. No basin has yet been found in which a limit to the number of wells it would furnish was not soon reached. The Dakota basin has a limit, and if it is possible to determine approximately what that limit is, no better work can be done than that.